

# MODERN NAVAL WARFARE



**GUIDE TO MODERN NAVAL WARFARE**



MODERN NAVAL WARFARE  
SSN-774 Virginia Class  
Guide to Modern Naval Warfare

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# **THE MODERN NAVAL WARFARE GUIDE**

A GUIDE TO THE WORLD AND HISTORY OF MODERN NAVAL WARFARE

Wave Ops

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# FOREWORD

In the long and storied tradition of maritime nations, few domains of human endeavor rival the complexity, intensity, and unforgiving nature of naval warfare. From the triremes that once carved their wake across the Aegean, to the multi-domain fleets of today—and the hybrid fleets of tomorrow—the sea has always been a theatre where technology, leadership, training, and human judgment converge under conditions of extreme uncertainty.

Naval warfare is not a single discipline—it is a layered and dynamic system of systems. It unfolds simultaneously across the tactical, operational, and strategic levels. It demands mastery of sensors and weapons, of navigation and communications, of intelligence and timing. It requires coordination across domains—surface, subsurface, air, cyber, and space—each with its own logic, tempo, and vulnerabilities. Above all, it demands people: trained, disciplined, and capable of making critical decisions in moments where hesitation can be fatal and clarity is often elusive.

There is no substitute for experience at sea. It takes years—indeed decades—of training, watchstanding, and operational exposure to begin to understand the battle rhythm of a warship, the weight of command, and the silent pressure of responsibility carried on the bridge and in the operations room. The sea does not forgive inexperience—and neither does the enemy.

And yet, here we are.

At a time when the complexity of naval operations continues to grow, when the pace of technological change accelerates, and when access to real-world training is both costly and limited, the challenge of realistically capturing naval warfare in a digital environment has long seemed insurmountable. Many have tried. Few have come close.

What makes *Modern Naval Warfare* remarkable is not simply that it attempts this challenge—but that it rises to meet it with an ambition and fidelity rarely seen outside professional military simulators.

This is not just a game. It is an experience.

It is immersive in a way that fundamentally changes the relationship between the player and the virtual battlespace. You are no longer an external observer issuing detached commands. You are inside the ship. You move between stations. You assume roles.

You feel the tempo of operations, the pressure of incoming threats, the constant need to prioritize, to decide, to act.

You become, in essence, a one-person crew—transitioning across combat systems, from sensor management to weapons employment, from situational awareness to decision-making—mirroring, in compressed form, the collective effort of an entire warship's company.

And in doing so, you begin to appreciate something that no textbook can fully convey: the orchestration of naval combat. The delicate balance between information and action. The necessity of discipline under pressure. The art of command. What is perhaps most striking is the level of realism achieved. The systems behave as they should. The environment challenges you as it would at sea. The decisions carry consequences that unfold in time—often irreversibly. In many respects, the fidelity reaches a level that would make even professional simulators pause—and reflect.

Of course, no digital representation can fully replicate reality. Something will always remain beyond reach—the salt in the air, the vibration of the hull, the human presence of a crew working in unison, the intangible weight of real responsibility. But what *Modern Naval Warfare* achieves is something profoundly important: it brings you closer than ever before.

Closer to the ship.

Closer to the decision.

Closer to the experience.

For professionals, it offers a new lens through which to explore and reflect upon the dynamics of naval operations. For enthusiasts, it opens a gateway into a world that is often hidden, misunderstood, or underestimated. And for all, it stands as a testament to what can be achieved when passion, knowledge, and technology converge with purpose.

As someone who has spent a lifetime at sea, in command, and in service of maritime security, I approach such claims with caution—but also with genuine admiration. *Modern Naval Warfare* does not merely simulate naval combat.

It respects it.

And that makes all the difference.

**Georgios Floros**

Vice Admiral (Ret.) Hellenic Navy

Former Deputy Chief of the Hellenic Navy General Staff

Senior Defense Advisor

## TO THE FEW WHO WILL READ IT

It wasn't long ago that we received a message from our publisher stating that it was final and irreversible. They were among the elite few—if not the last—of their genre who continued publishing a limited range of their products in *physical copies*, and recently, they abandoned this delivery process.

Designing MNW inside an office packed with vintage boxes of simulators originating from the late '80s, '90s, and '00s has been an essential part of our inspirational supply chain.

The simulation market has changed significantly from where we left it in our youth as players, and later on, in our early professional careers as suppliers.

The game industry has long passed its adolescence. The market produces thousands of titles every year, and each and every time, the consumers are becoming more title-thirsty and simultaneously more demanding.

Constant technological advances in *real-time* graphics, SDKs, and toolsets are the basic reasons behind partially supporting such increased demands, both in delivery times and product quality.

However, regardless of how *on-rails* game R&D has evolved, quality titles are an endangered species—both in the mainstream and indie industries.

The MNW development experience has proven something that may not be obvious, but is surely expected: the research and development of a *high-fidelity* simulator is a challenging task. It always has been.

With advances in graphics capabilities, the *sim-dev-team* is implicitly obliged to push the detail barrier even further, with the added risk that this push must correspond to reality. There is no room for excuses if something looks off.

Although realism is obviously the guide to the R&D of a simulator, the *sim-dev-team* has to become inventive in disguising the technological—and, in some cases, policy-related—limitations that arise along the way.

Regardless of the fact that the delivery times of games are constantly increasing over the decades—from a couple of months in the '80s to several years today—*high-fidelity* simulators always diverged from this trend.

Defining whether the development of a *high-fidelity* simulator is delayed or not is a matter of perspective—one we have yet to clearly articulate.

After surviving one pandemic, six conflicts waged, three ceasefires, five *Virginia-class* SSNs commissioned, one R&D team assembled in Greece, more than a couple of hundred of thousand lines of source code written and two babies born, we can confidently say that the secret behind the successful delivery of MNW is “*to endure.*”

By delivering to you *Modern Naval Warfare* we are not just providing you an opportunity to re-experience—after almost twenty years of absence—the lost art of modern military naval simulation but we are also sharing with you our perception of a quality product.

A kid examines the shelves stacked with cardboard boxes very thoroughly, and there it is—standing in plain sight. Their hands can barely reach it.

*“Dedicated to the kids who stared the boxes from below.”*

**Dimitris Maslarinos**

# WHAT IS A SUBMARINE?

Before getting into the subject, we need to define what a submarine is. Why, will you ask?

Do you consider a ninja with a straw waiting for the emperor to come near the ridge of a river a submarine or the story of Alexander the Great getting underwater into a glass bell the first submariner? In fact, some countries and historians were prone to take ownership of the invention of the submarine using some events as proof, so we will first need to have a proper definition of what makes a submarine a submarine!

We will define a submarine as:

- Man-made,
- Using an autonomous propulsion (manned or not),
- Capable of diving and surfacing by modifying its buoyancy (ballast),
- Capable of navigating underwater (rudders, planes),
- Capable of staying underwater for some time,

Submarine or submersible?

Technically, the difference between a submarine and a submersible is that a submarine spends most of its time underwater, while a submersible navigates mostly on the surface and goes underwater only when necessary. Currently, the submarine manufacturers use a different definition; the word submarine is reserved for the military and submersible for the civilian market, but the USN still uses the prefix SS (Ship Submersible) in its hull classification.

First, for those not familiar with the long history of submarines around the world, we will start with a short primer.



# GENERAL HISTORY OF THE SUBMARINE

Writing about submarine history is not an easy task; there are thousands of books about their history, with an H or h, and almost every boat captain has one or more books, a thesis, or an essay. So, trying to resume more than 400 years of technical progress and achievements in a few pages is almost an impossible mission! So, let's start; we love challenges!

## FROM THE FIRST MENTION TO 1863 : THE MANNED PROPULSION ERA

Historically, William Bourne, an Englishman in his book *Inventions or Devises*, described the first submarine concept in 1578. This submarine used oars for propulsion and a system decreasing / increasing the internal volume of the submarine to make it dive / surface. It was never built, but this concept is considered as the first submarine.

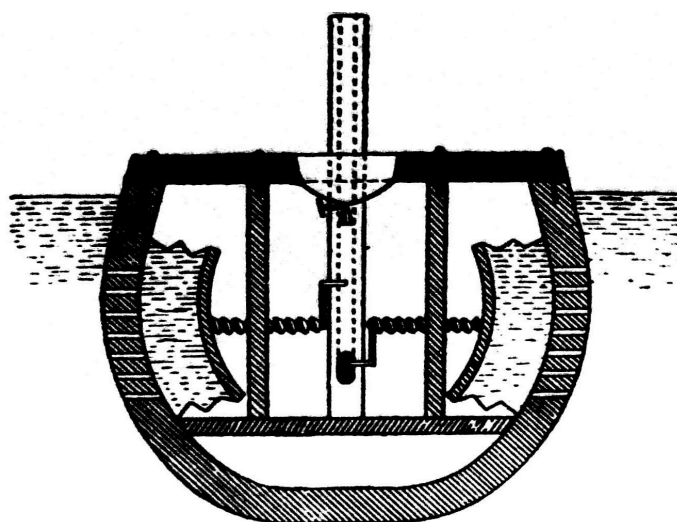


Figure 1: William Bourne concept of ballast.

A Dutchman, Cornelius Drebbel, in 1620, while he was working for the Royal Navy, made the first recorded attempt at a real submarine; it was a hand-powered, leather-covered

rowboat that could submerge for short periods of time (1 to 3 hours). He built and tested three submarines between 1620 and 1624, but the British admiralty never found a practical interest in those.



Figure 2: Cornelius Drebbel submarine.

In 1775, David Bushnell designed the Turtle, the first military submarine used in the American Revolutionary War, though it was unsuccessful in its attempt to sink the HMS Eagle, a British warship anchored near Staten Island in the New York harbor.

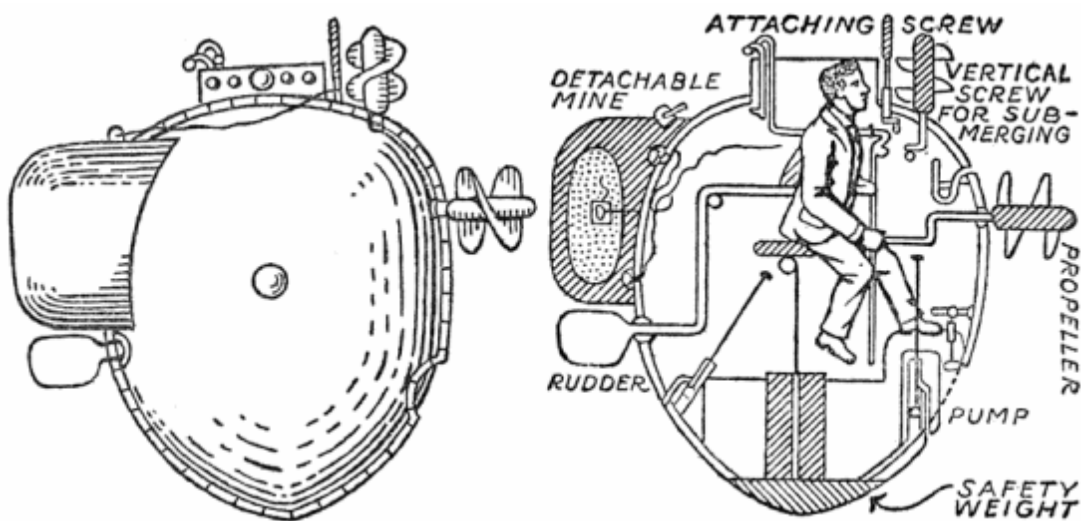


Figure 3: David Bushnell Turtle.

Between 1793 and 1796, Robert Fulton, an American inventor, developed for the French the Nautilus, a man-powered submarine equipped with ballasts, dive planes, an observation dome (the first submarine sail), and a snorkel to provide air to the crew. After

some iterations, the submarine remained submerged for more than 4 hours. After a few years of sailing, the Nautilus didn't get the interest of the French Navy, and in 1801, he went to work for the British, developing some new naval weapons.

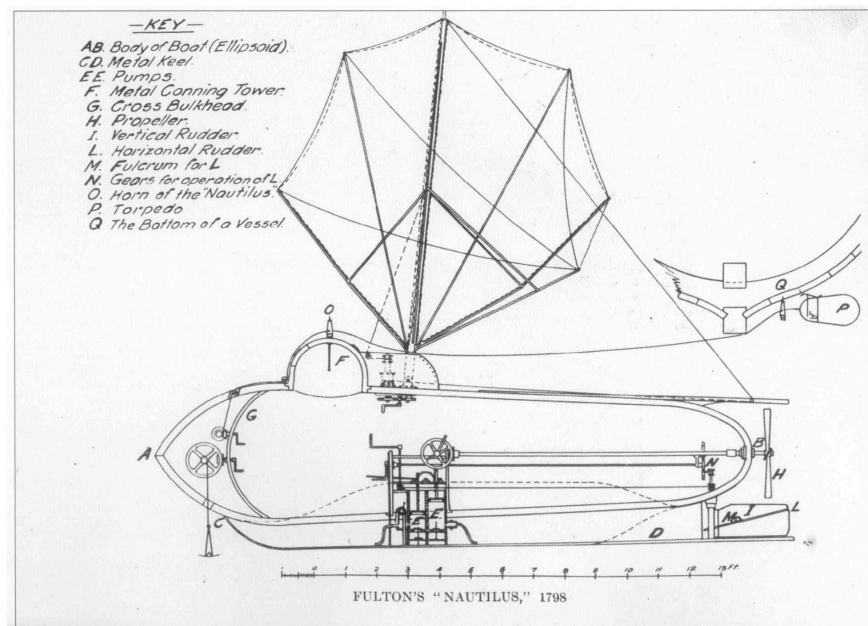


Figure 4: Robert Fulton Nautilus.

Submarine development took a significant step forward during the American Civil War (1861-1865). The CSS Hunley, a Confederate submarine, was the first to sink a warship, the USS Housatonic, in February 1864 during the blockade of Charleston harbor by the Union forces. The submarine used a spar torpedo, a pole with an explosive device at the end. Unfortunately, the Hunley was lost with all hands. One hypothesis is that the submarine was too close to the detonation point and sustained heavy damage from the explosion.

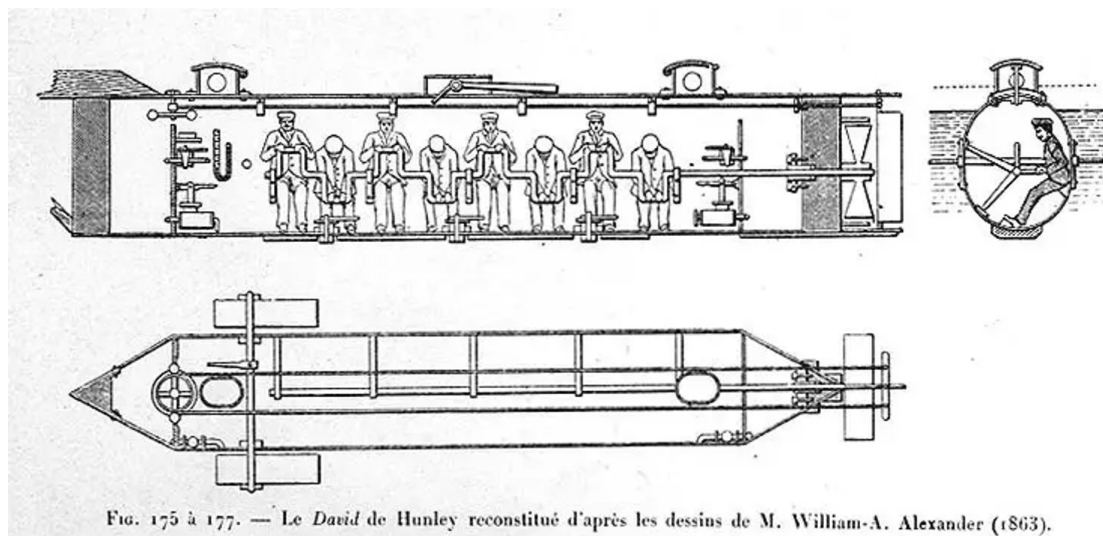


Figure 5: CSS Hunley.

## FROM 1863 TO 1914: FIRST ENGINE, TORPEDO, AND UNDERWATER ECHO-RANGING APPARATUS.

1863 was the year when the first mechanized power propulsion was installed in a submarine. The French submarine *Plongeur* was designed by Captain Simon Bourgeois and engineer Charles Brun. The engine was powered by compressed air. The engine was able to propel the submarine for 9 km (5 nm) at a speed of 7.2 km/h (4 knots).

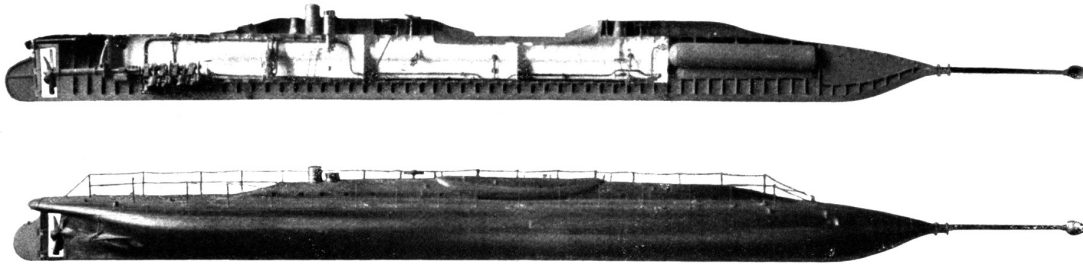


Figure 6: Submarine *Plongeur*.

The modern torpedo as a self-propelled underwater missile was invented by Robert Whitehead, an English engineer, in 1866. Whitehead's design could travel underwater to strike enemy vessels, a revolutionary development at the time. Whitehead's torpedo was propelled by a compressed air engine and had a rudimentary depth control mechanism, allowing it to travel at a set depth.

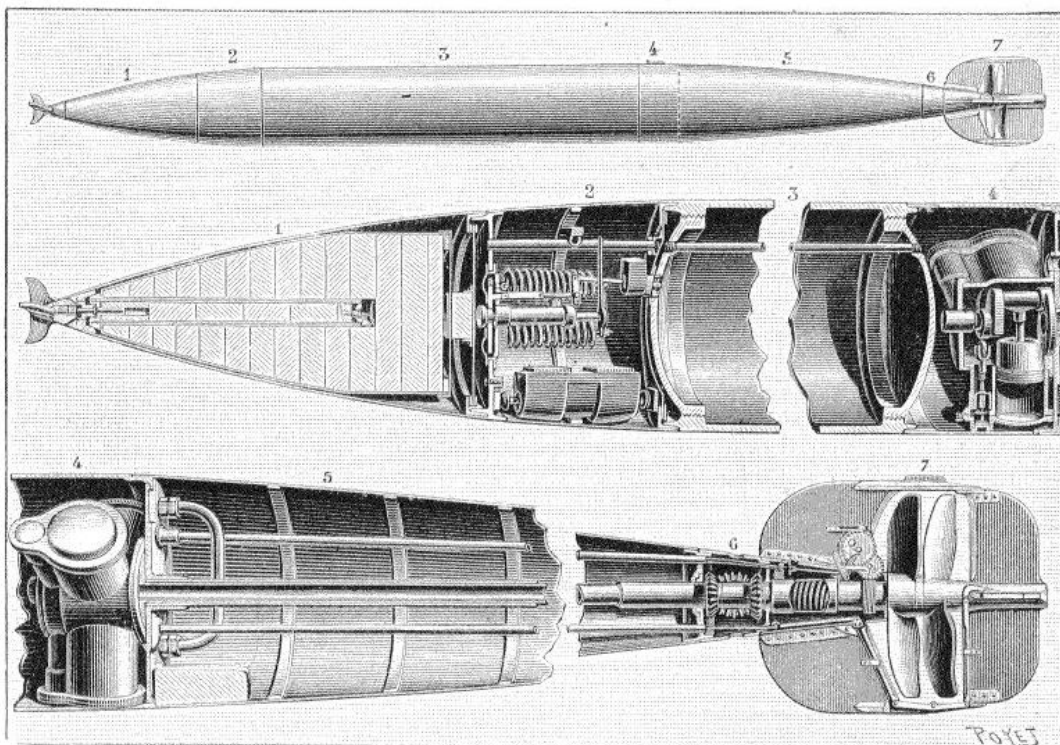


Fig. 1. — Torpille automobile Whitehead. — 1. Magasin. — 2. Chambre à secret. — 3. Réservoir d'air comprimé. — 4. Chambre des moteurs à air comprimé. — 5. Flotteur ou chambre de flottaison. — 6. Mécanisme de commande de rotation des hélices. — 7. Hélices et gouvernails.

Figure 7: Whitehead torpedo.

His design inspired navies worldwide and became the basis for future torpedoes. Their first use was to defend ports; then they were mounted on ships (torpedo boats), and then on submarines.

By the mid-1890s, the introduction of gyroscopes into torpedoes improved directional control, enabling torpedoes to maintain a straighter course.

A few years later, the first electric torpedoes were developed, allowing quieter operation (no visible plume of steam from the surface), but they were limited in range and speed compared to compressed-air versions.

The end of the 19th century and the beginning of the 20th, saw a fast-paced technological addition to the submarines, for example:

- Hippolyte Marié-Davy designed the first naval periscope in 1854: a vertical tube with two tiny mirrors set at each end at 45°.
- In 1886, the Swedish submarine Nordenfält, was the first to use electric propulsion.
- 1887, the Holland VI, future SS1 Holland of the USN, was fitted with a gasoline engine and is considered the first “modern” submarine,
- 1909, the French submarine Mariotte was the first to be fitted with a diesel engine.
- 1902 Simon Lake made the first use of a periscope aboard a US Navy SS1 Holland.
- 1912, following the Titanic disaster, research was done on underwater echo-ranging, leading to the development of the first system to detect underwater icebergs.

## **FROM 1914 TO 1945 : THE GOLDEN AGE OF THE SUBMARINES**

The real operational history of the submarines as a constituted force started in 1914. The Austro-Hungarian, German, and Bulgarian from 1914 to 1918 went from 20 to 351 submarines; 217 of those were lost at sea. Those submarines were slow compared to the military ships at the time (15 knots). Their submerged speed didn't exceed 5 knots and they had limited visibility through the periscope, unable to follow and attack warships while submerged. They had few successes, but it was more luck than anything else, being at the right spot at the right moment to launch a torpedo at a warship like the U-9; in September 1914, her captain sank three British cruisers in one hour, using 6 torpedoes, killing 1459 sailors.

Starting in 1915 as what is known as the War on Commerce or unrestricted submarine warfare, they were used to attack and sink any merchant ship cruising from or to the British island. This led to the sinking of the RMS Lusitania in 1915, which helped bring the United States into the war.

German submarines were also used to lay minefields at the entrance of ports with poor results since they were able to carry only a dozen mines at the time. Submarine warfare evolved and moved from the coast of England to the Mediterranean Sea to the coast of the US.

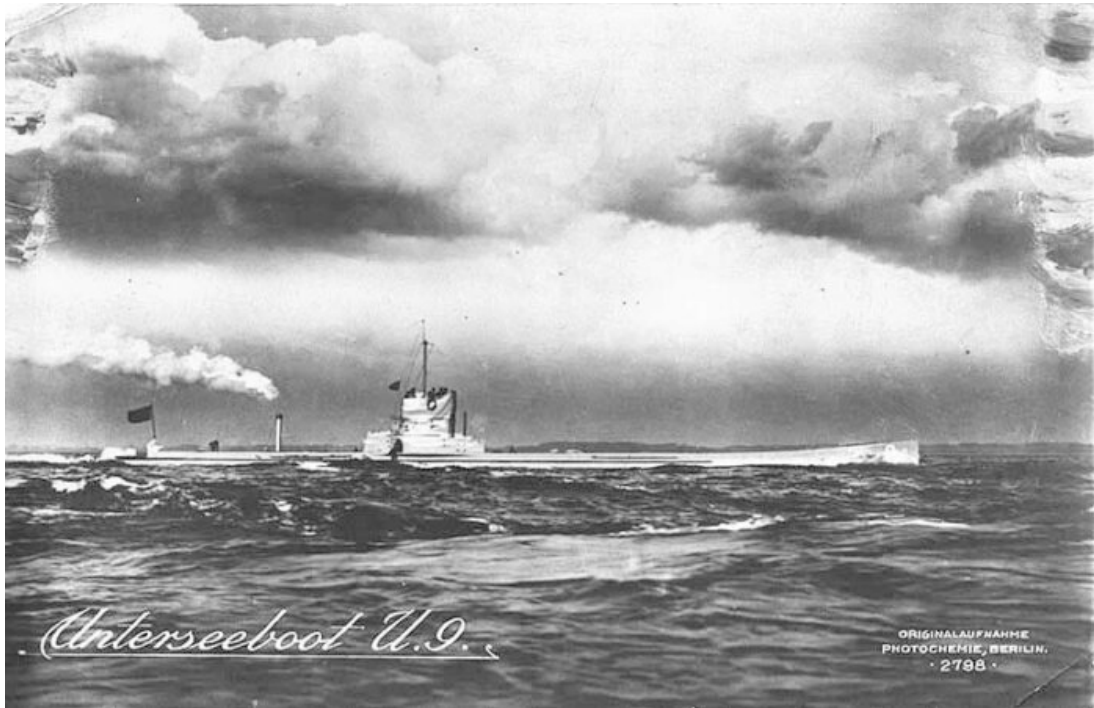


Figure 8: Submarine U-9.

Few countermeasures were available at the time against submarines, such as speed, zig-zag, disruptive camouflage known as the dazzle camouflage, convoys, maritime patrol aircraft or blimp, anti-submarine nets and minefields, and disguised armed cargo ships known as Q-ships, which were used on both sides to lure submarines.

Depth charges were invented in 1910 and first deployed aboard warships and Q-ships around 1916; first ships were carrying only 2, then 4, and to 30 to 50 at the end of the war. The first kill of a submarine using depth charges occurred in 1916 by a British Q-Ship against the U-67.

Submarine underwater detection using sound was launched at the start of the war, with some breakthrough developments in 1915, but it was only in 1917 that the first ASDIC (named after the Anti-Submarine Division of the British Naval Staff) was devised and experimented with in 1918.

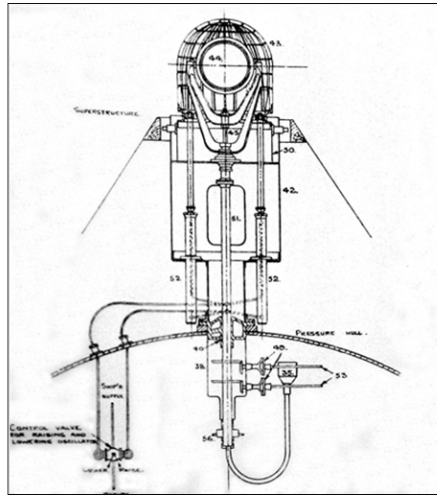


Figure 9: ASDIC.

At the end of 1917, the 140 German submarines had sunk 30% of the world's merchant fleet, and by the end of war more than 5000 Allied ships were destroyed, mainly around the British coasts, the Mediterranean Sea, and the Atlantic.

### 1918-1939 INTERWAR INNOVATIONS

In 1919, article 188 of the Treaty of Versailles totally restricted Germany's ability to build, possess, or use submarines, but by the 1930s, they were secretly rearming (working in the Netherlands or with the Soviet Union), eventually producing advanced U-boats using their experience of the WWI. Between the wars, submarine technology continued to evolve. Both diesel-electric propulsion and hull designs were refined to allow submarines to dive deeper and operate longer. Periscopes, SONAR/ASDIC, and improved torpedoes were introduced.

### WORLD WAR 2

The story of submarines until the end of World War II is all about rapid innovation, shifting strategies, and evolving technology.

During WWII, submarines played crucial roles for both the Axis and Allied powers. German U-boats were the mainstay of the Battle of the Atlantic, a campaign to sever Britain's supply lines as they had tried during WW1. Using "wolf pack" tactics, U-boat groups coordinated attacks on Allied convoys, causing massive losses in the early war years.

The Allies countered by perfecting sonar devices, radar, long-range patrol aircraft (such as the PBY Catalina, Beriev Be-6, or English Avro Lancaster MP), and anti-submarine tactics and technologies. By cracking the Enigma code, the British were able to predict U-boat movements and turn the tide in the Atlantic.

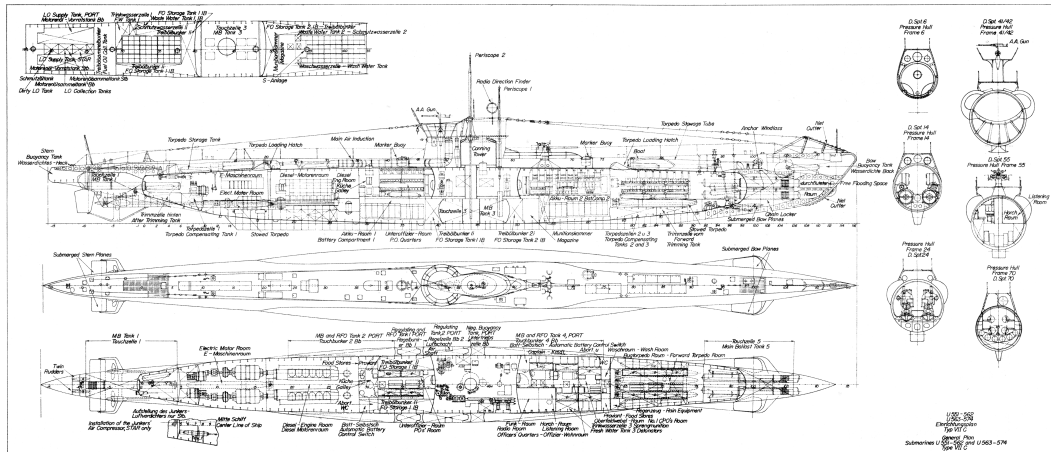


Figure 10: German U-boat Type VIIC.

In the Pacific, the USN submarine fleet after the Pearl Harbor attack in 1941 had 55 submarines, 18 in the Pacific. This fleet had a lot of problems at the start of the war with obsolescence, training, aggressiveness of their CO, and torpedo malfunctions (Mk-14), but all those problems were resolved, some late in the war, fortunately for the Americans, the Japanese side didn't see the US submarines as a threat and didn't put any effort in the ASW fleet.



Figure 11: USN Gato class submarine.

Operating primarily from bases in Pearl Harbor, Midway, Fremantle, and Brisbane, they targeted Japanese shipping lanes, were used as reconnaissance assets and for Special Force insertion (Marines Raiders), and also as pickets to rescue downed pilots.

The submarine force paid a high price 375 officers, 3,131 (20% of the total submarine fleet personnel), and 52 boats were lost at sea, but in 1945, the Japanese merchant fleet was decimated, losing around 1113 ships for a total of 4,779,902 tons (around 50% of all ships sunk by the US in the Pacific) at what we can add 201 warships from Japanese Navy (IJN).

Some technologies were improved, like the periscopes; almost all submarines at the end of WW2 had two installed, one for attack (with high magnification for precision targeting) and a second for observation (wider field of view for better situational awareness).

Acoustic torpedoes were introduced by the Germans in early 1943 and upgraded until the end of the war, but the Allies developed countermeasures like the Foxer or Fanfare noisemaker. Studies revealed at the end of the war, that only 10% of those torpedoes hit their targets (77 of +700 launched).

Radar was widely used by submarines and anti-submarines forces (ships and patrol aircraft), and as usual, countermeasures were developed shortly after the introduction of this new method of submarine detection (snorkel, radar detector, ...)

## **THE MODERN AGE OF THE SUBMARINE, FROM 1945 TO THE PRESENT.**

By the end of WW2, submarines had become one of the key elements in naval warfare alongside aircraft carriers. Submarines reshaped naval strategy and proved the power of stealth and surprise in warfare, leaving a lasting legacy on global military tactics and technology.

Germany was leading in design technology with the Type XXI. It was the first real submarine with a diving speed greater than the surface one, a slick hull without deck guns; she still had two sail-mounted turrets for air defense.

By 1945, submarines had gone from almost experimental, fragile boats into critical tools of naval warfare. The war demonstrated their potential for both strategic and tactical operations, influencing post-war submarine design, including the development of nuclear-powered submarines. The innovations and technological advancements laid the groundwork for the modern submarines we know today, which are faster, stealthier, and equipped with advanced weaponry.

The two major developments occurred in the early 50's and 60s with the introduction of nuclear propulsion with the Nautilus in 1954 and, in 1953, the Albacore AGSS-569, the first submarine built with a hydrodynamic hull.

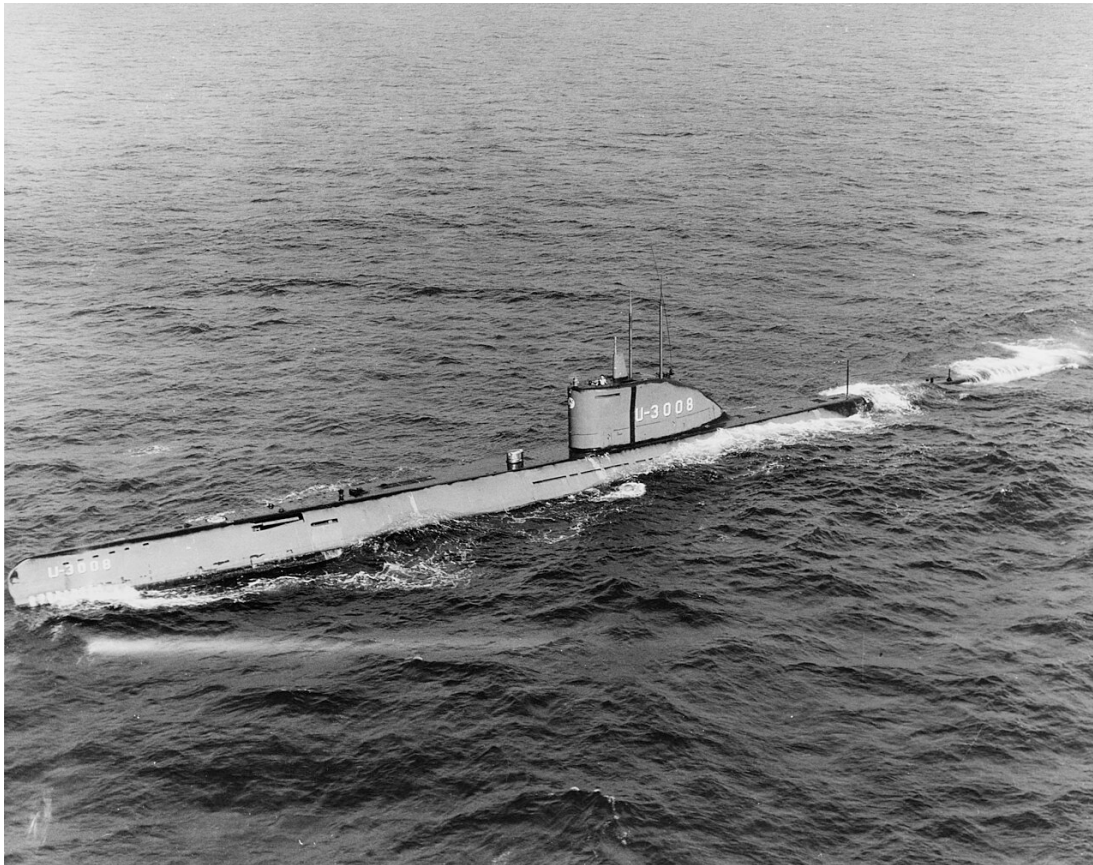


Figure 12: Type XXI submarine.

## THE NUCLEAR AGE

The first idea of using a nuclear reactor for submarine propulsion was proposed by Dr. Ross Gunn, head physicist at the Naval Research Laboratory, in 1939, after a meeting with Fermi in Washington. He got support from Admiral Bowen, but the war stopped all research and investment on this topic, focusing all the effort on the Manhattan Project. The secrecy around the nuclear bomb, even at the end of WW2 prevented access to some installation and research documents, slowing the research for a naval reactor.

In 1948, a young captain named Rickover was put in charge of the project for the navy. Ending his naval career after 63 years, Admiral Hyman Rickover, often called the “Father of the Nuclear Navy,” played a pivotal role in developing the U.S. Navy’s nuclear propulsion program, leading to the launch of the first nuclear-powered submarine, USS Nautilus, in 1954.

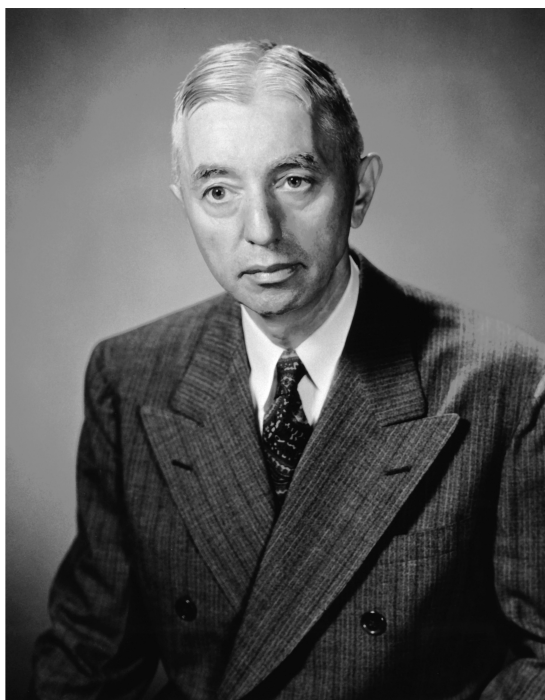


Figure 13: H.G. Rickover (1955).

### THE NAUTILUS, THE FIRST NUCLEAR SUBMARINE

In 1951 the US Congress authorized the construction of the first nuclear powered submarine the Nautilus that was supervised by Rickover. She was commissioned on 30 September 1954. Her hull was inspired by the German Type XXI submarine, and she was powered by an STR S2W nuclear reactor developing around 13,000hp.

She was the first submarine to reach the North Pole underwater during Operation Sunshine in 1958.

She was decommissioned in 1980 and became a museum at the Submarine Force Library and Museum in Groton.

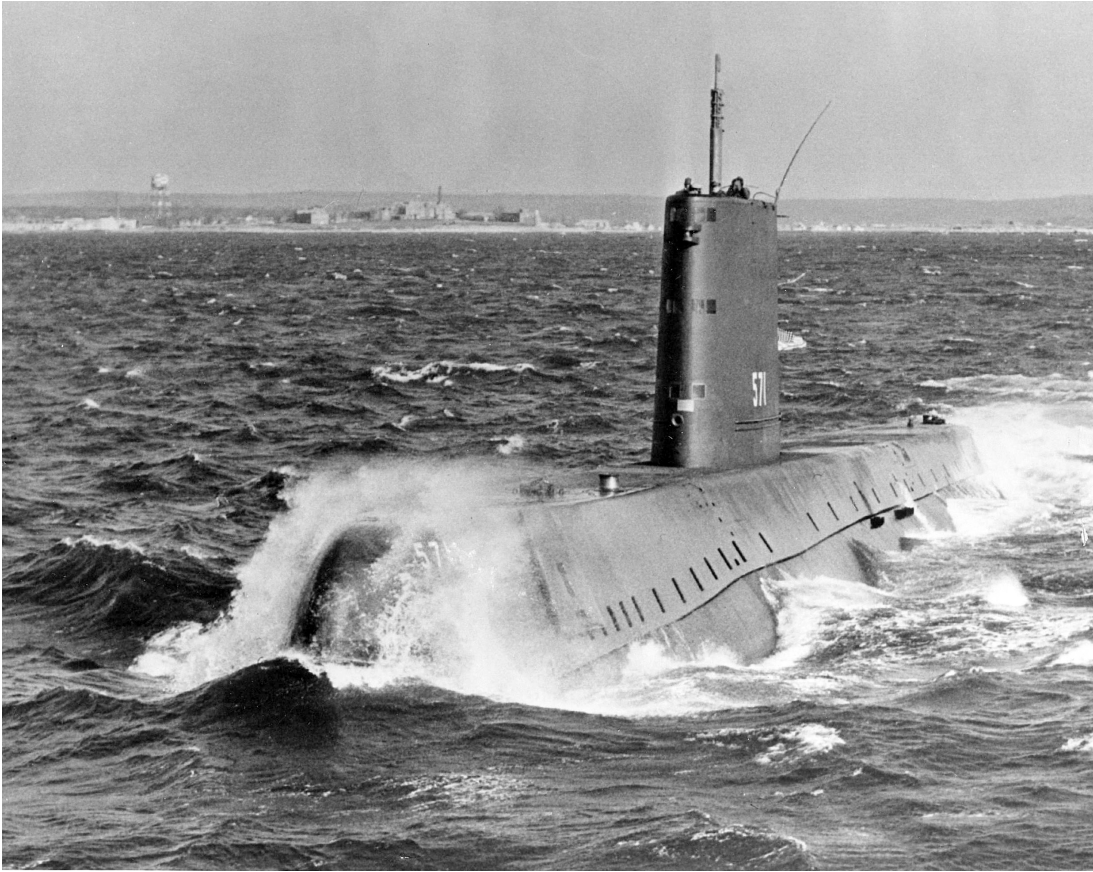


Figure 14: USS Nautilus.

### THE ALBACORE REVOLUTION

Launched in 1953, the innovative U.S. Navy experimental submarine USS Albacore (AGSS-569) was a test platform for hydrodynamic and technological developments.

Since it was a test bed and to get funded, the AGSS\_569 wasn't fitted with torpedo tubes.

The albacore was equipped only with diesel engines (two General Motors EMD 16-338 "pancake" diesel engines, each producing 1,000 bhp (817 kW) at 1,600 rpm) and batteries, allowing it to reach an underwater speed of 33 knots for a short time. Particularly with regard to underwater speed, its groundbreaking layout changed all future US submarines.

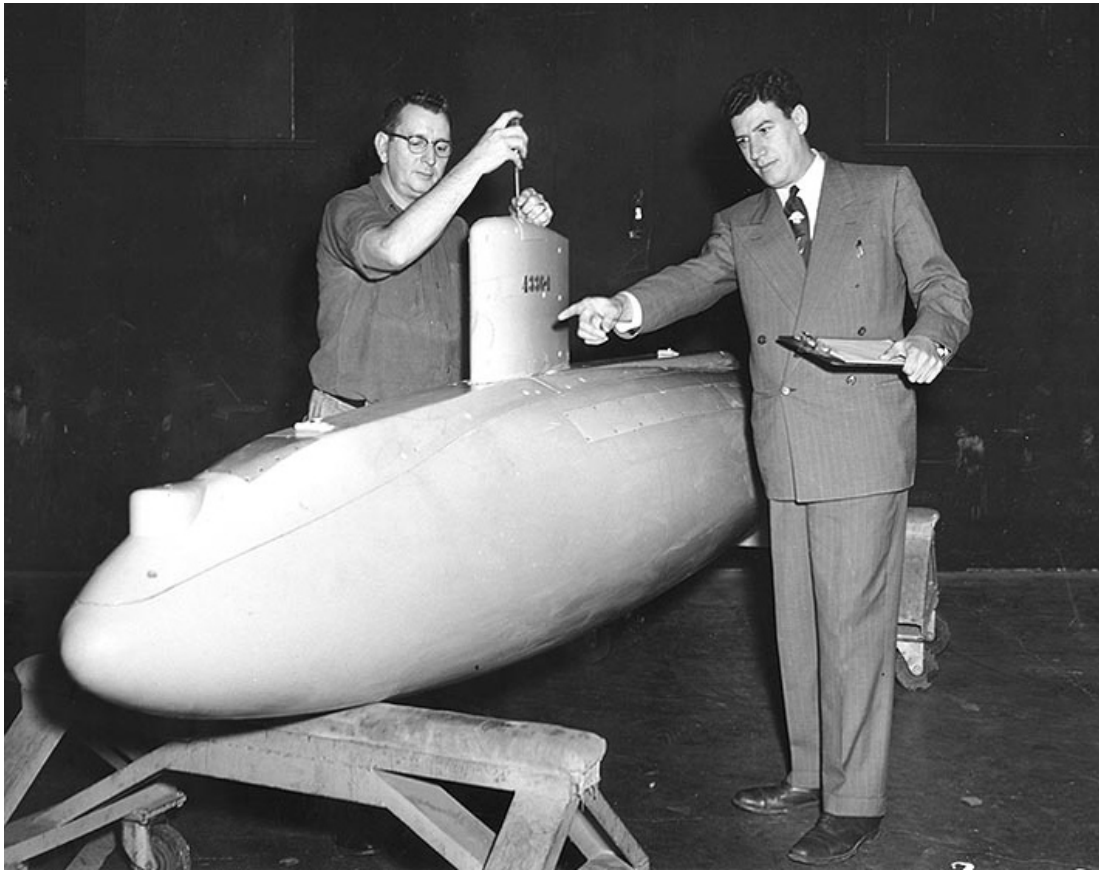


Figure 15: Albacore model.

Unlike previous designs, which were modeled from surface ships and were less effective underwater, this hull form was a radical departure from the norm. The first submarine using a teardrop-shaped hull designed for hydrodynamic efficiency underwater, its simplified, rounded form using a single-pressure hull, instead of a double-hull design utilized in previous submarines, drastically lowered drag, enabling it to travel faster and maneuver below the surface.

X-shaped stern control surfaces (tail fins) invented by the Albacore enhanced control and stability during fast bends. Its sophisticated controls for dynamic depth changes enable it to operate effectively under diverse depth and speed profile.



Figure 16: Albacore X surfaces control.

Engineers also looked at ways to cut hull and machinery noise from the submarine. These tests guided the construction of quieter, more stealth-oriented submarines able to avoid adversary acoustic detection. All the new submarines in the USN incorporate innovations from the Albacore.

The infant of the Nautilus and the albacore was a new class of submarine, the first modern one incorporating the PWR reactor and the tear-drop hull shape, the Skipjack class starting in 1956. From there, a successful series of classes (Thresher/Permit, Sturgeon, Los Angeles, Seawolf, and Virginia) was developed, each adding the most modern technologies available at the time but with a cost per unit reaching this day a few billion USD.

At this point, the USN introduced the Acoustics-Rapid COTS Insertion (A-RCI) program in the 90's. This new approach uses Commercial Off-the-Shelf (COTS) equipment to reduce the price of the SONAR suite.

But we should not forget the other types of submarines; not all are SSNs; only six nations have nuclear submarines at this time: the USA, Russia, the UK, France, China, India, and North Korea.

Some countries like Brazil currently have programs to develop their own nuclear-propelled submarine; Australia, with the AUKUS alliance, will get some SSNs in the future (American, British, or ....).

## THE FOUR TYPES OF MILITARY SUBMARINES

Modern submarines are usually split to 4 main categories.

### SSN - SHIP SUBMERSIBLE ATTACK NUCLEAR

SSN, Fast Attack or Hunter Killer are submarines designed to hunt and destroy other submarines and surface ships.

### SSBN - SHIP SUBMERSIBLE BALLISTIC NUCLEAR

Those boats are loaded with ICBM (Intercontinental Ballistic Missile) equipped with one or more nuclear warheads. SSBNs are part of the Continuous Deterrence at Sea (CDAS); their mission is to hide in the deep sea, at low speed, for 3 months at a time, waiting for an order that no one wants them to receive. They are usually the quietest boats in a fleet.

### SSGN - SHIP SUBMERSIBLE GUIDED NUCLEAR

SSGN is a type of special submarine, unlike SSN or SSBN. They store cruise missiles or anti-ship missiles, and their mission is to attack land targets such as the American Ohio class (which was converted from SSBN to SSGN). The Russians also have some SSGN submarines like the Graney class (Project 885 Yasen / Yasen M.) equipped with Zircon, Kalibr, or Onyx missiles that can attack ships or land targets.

### SSK - SHIP SUBMERSIBLE ATTACK CONVENTIONAL

Thirty-nine countries are currently operating non-nuclear submarines using either diesel/electric propulsion or Air Independent Propulsion (AIP); they are classified as SSK. According to numerous sources, there are between 260 and 288 SSK in service actually.

Those submarines use either diesel/electric or Air Independent Propulsion (AIP).

In the inventory of submarines, there is a particular case of the midget ones. A few countries possess some; the most notorious are North Korea (Yono class), Iran (Nahang class), and Russia (Losharik). Their efficiency was proven in 2010 when the South Korean corvette Cheonan was presumably sunk by a Yono.

As you just read, the history and evolution of submarine design in the last 200 years is fascinating, coming from a simple wooden barrel to the mastodon that is the SSBN. In the next section, we will discuss the major components of a submarine. Modern submarines are as complex as a space station, and the number of components required to operate them is quite large, ranging from the propulsion to the environmental control, cooling, hydraulics, berthing, and storage. Let's have a quick look at the major systems.



# ANATOMY OF A MODERN SUBMARINE



Figure 17: Virginia class submarine.

As we wrote earlier, a modern submarine is so complex that even 400 pages will not be enough to describe all its systems and design constraints. So we will present only the major ones: Hull, Sail, Propulsion, Steering, and Command and Control Center.

## HULL

Modern submarines use either single hull (pressure hull) or double hull (outer hull and pressure hull), the tendency is now to have only pressure hull.

The pressure hull is the inside hull that protects the crew and all the equipment.

The hull is made of a high-strength steel alloy like the HY-80 (80 refers to the maximum pressure this alloy can sustain, in this case, 80,000 Pounds per Square Inch PSI or, for the rest of the world, 5625kg/cm<sup>2</sup>). Pressure hulls are typically cylindrical because this form distributes the pressure evenly.

There are some other high-strength alloys like the HY-100, 120, or even 130, but those are difficult to shape and weld. Some countries, like the USSR, used Titanium for the hull, but the cost was high, and titanium is not as tensile as steel. As a result, the hull developed micro-cracks during each dive, lowering the maximum safe depth for the next dive.

The pressure hull should have as few openings to the sea as possible, like crew or weapons hatches to access the submarines, torpedo tubes, reloadable countermeasures launchers, water cooling inlets/outlets for the propulsion, garbage or brown/black waters disposal, antenna or tower array access, ... Those are the weakest parts of the submarine's integrity and must be carefully designed.

Submarines have to stay above the crush depth, which is the depth at which the hull will collapse, instantly killing the crew and destroying the submarine. This depth is theoretically computed using models so that it can be deeper or shallower.

Most of the submarines have an outer hull in addition to the pressure hull.

Some equipment, like the ballast tanks, is between those two hulls, used to control the submarine's buoyancy and allow it to dive or surface. Older Russian submarines used double hulls to add protection against light torpedoes and reduce submarine noise.

## BLOCKS AND RAFTING

The current trend for submarine construction is to build them using blocks and raft mounting.

The block method divides the submarine into sections rather than first building the entire hull. This method offer few advantages: different blocks can be built in parallel and then assembled and all necessary equipment can be installed, cabled, and tested without with ease.

Rafting is an increasingly used building method. The raft, a framework, is fitted with all the equipment and then slides into the block. The main advantage is that the trades have access to almost all areas of the raft before it is installed.

Rafts are also isolated from the hull using dampers (rubber pads), reducing self-generated noise passing from the equipment to the hull.



Figure 18: Raft inserted into a Virginia submarine.

Dampers are also used between the motor, the shaft, and the propellers to limit vibrations.

## SAIL

The Sail or conning tower is the most iconic part of a submarine. It can be made of steel, aluminum, or fiberglass and houses all the masts, navigation lights, and some specialized sonar. There is also a bridge/observation deck to host some watches and sometimes security details when the submarine is surfaced. Some submarines had doors at the bottom of the sail to easily access the top of the hull. The sail hosts all the masts of the submarine, periscopes, communications antennas, ESM and snorkel. Modern submarines use non-penetrating masts, meaning the masts do not penetrate the pressure hull. All their assembly is confined to the sail and the data they receive, or transmit, is electronic. Those types of mast have numerous advantages over classic ones. Since there is no well to store them within the submarine hull, there is no longer a need to have the Combat Information Center (CIC) below the sail, for example, the CaCC of the Virginia is located on the 2d deck. There is also less hull penetration, resulting in better hull integrity in the event of a collision when using the periscope. The data collected can also be distributed to all stations if necessary; the image from optical periscopes, for example, unless they are equipped with a forward camera, can be seen by the person looking through it.

The sail on a submarine, with all its advantages, causes drag and, in turn, creates lift, which can lead to a large roll at high speed called a “snap roll.” Also, the propeller can

ingest the water flow of the sail, increasing low-frequency noise. That can be reduced by adopting a pump jet propulsor.

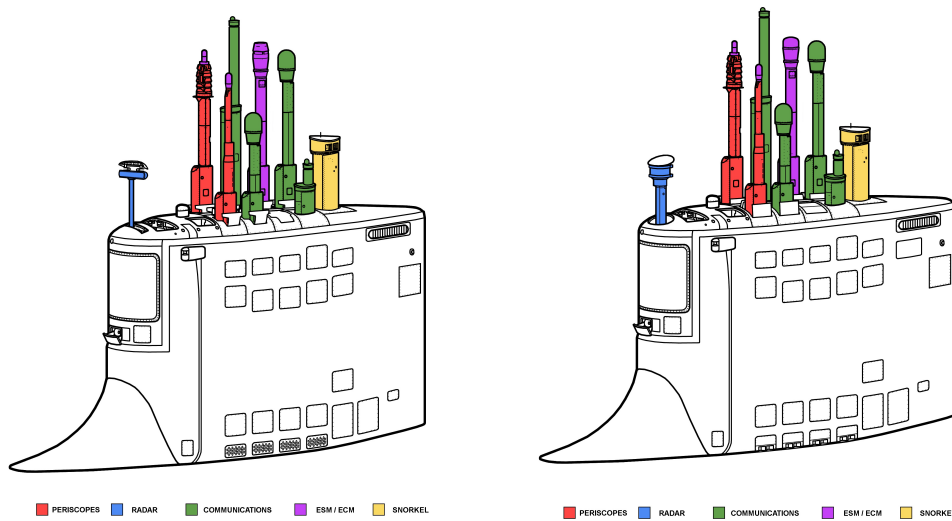


Figure 19: Sail of the Virginia class blocks 1-3 left and block 4 right – (c) 2022 Richard Stirn.

## CONTROLS OF A SUBMARINE – BALLASTS, RUDDERS, AND DIVE PLANES

### BALLASTS

Submarine buoyancy refers to the force that allows a submarine to float or sink in water, controlled by the displacement of water. A submarine achieves neutral buoyancy when the weight of the displaced water equals its own weight. This is controlled through ballast tanks, which can be filled with water to increase weight, causing the submarine to sink, or filled with air to reduce weight, allowing it to rise. By adjusting the amount of water in these tanks, the submarine can maintain precise control over its depth and stability in the water.

There are two types of ballasts: The main ballasts and the Depth Control Tanks (DCT) or Trim tanks. Those DCT are used for example to balance the submarine when she had launched weapons and lost some weight or when the water density change at the depth she sail.

## RUDDER AND DIVE PLANES

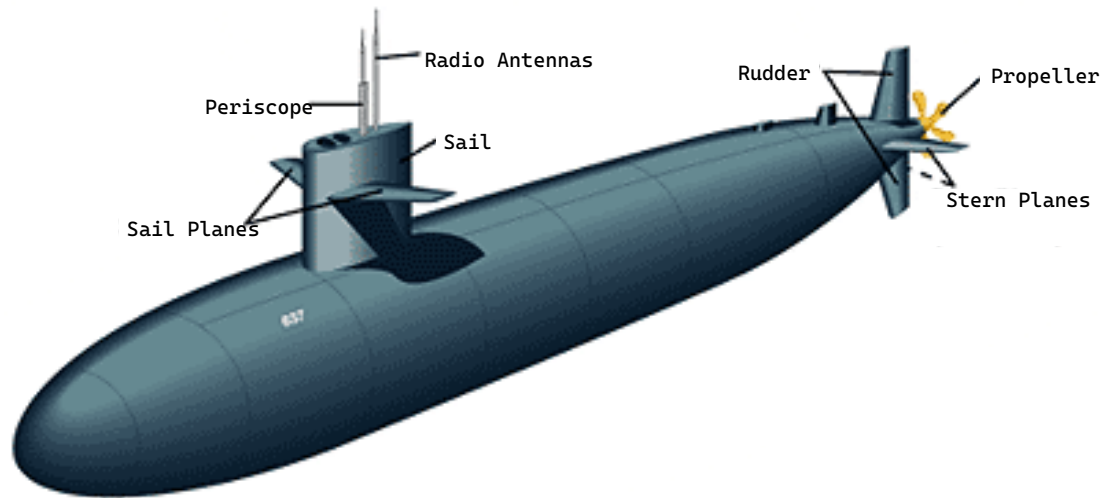


Figure 20: Submarine control surfaces.

A submarine is controlled almost like a plane, using rudder and hydroplanes (the elevators in a plane).

- **The Rudder:** Those vertical planes steers the submarine left or right (yaw control). Positioned at the stern, it helps the submarine change direction horizontally. The rudder works much like a ship's rudder.
- **Dive Planes:** Located either at the bow or on the sail of the submarine (in that case, they are called sail planes) and at the stern of the boat. Dive planes control the submarine's vertical movement (pitch control). They can be angled to direct the submarine up or down.

Using the dive planes to change depth rather than the ballasts is called dynamic diving. Bow planes are typically located at the front of the submarine, near the nose, and are often used to control pitch and help the submarine dive or surface. Stern planes are located at the rear, typically near the rudder. Older SSBNs used to have sailplanes because it was easier to maintain the depth near the surface to launch their missiles. The advance of electronic, precise spatial positioning and piloting-by-wires made this configuration obsolete in modern submarine.

A new configuration in rudder/planes design is used on some advanced submarines, most notably by German Type 212/214, Norwegian Ula-class and most recent SSN like the Virginia or Barracuda class. The X-Rudder or Diagonal Cross Layout.

This layout places the control surfaces diagonally in an "X" shape, rather than vertically and horizontally. Since no single fin sticks directly downward (as in A-rudders), the X configuration has less vertical protrusion, making it safer in shallow environments. The X-rudder can provide superior control in all directions, especially for precision movements in shallow or confined waters (harbors or under ice). It allows for combined pitch and yaw control, enabling tighter turns and more complex motion profiles. X-rudders may create less hydrodynamic noise, making the submarine quieter a critical factor in stealth operations.

Unlike older cross configurations, the moving parts are isolated such that the loss of one element results in the loss of only 25% of total control in one plan (vertical or horizontal), while the loss of one element in the older system results in the loss of 50% in the affected plan.

But the X configuration is not without drawbacks, the control algorithms and mechanical linkages needed to operate the X-rudder are more complex than traditional systems. It also results in higher maintenance requirements.

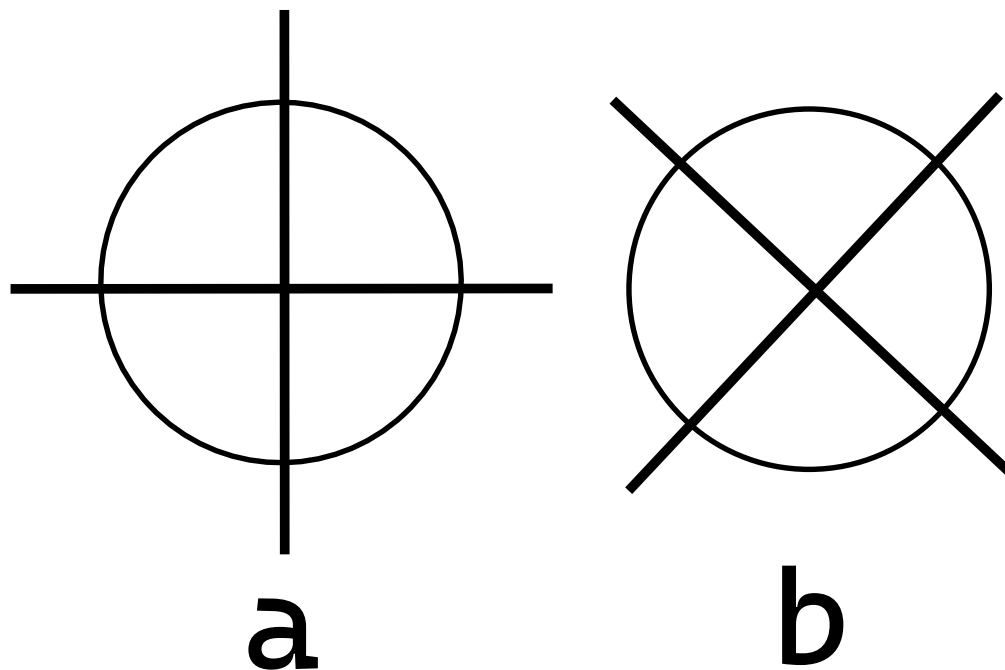


Figure 21: Legacy planes (a) vs X planes (b)

## PROPULSION

In the modern age, as we saw earlier, two main types of propulsion exist: conventional and nuclear. Conventional is the most used since it's relatively cheap to design, use, and maintain.

Conventional propulsion can be subdivided into two categories :

### CONVENTIONAL (DIESEL AND BATTERIES)

As we saw earlier in the history of submarines, the most used propulsion for more than 50 years was diesel engines coupled with batteries. This combination was, at the time, the best any navy could afford, but it had many inconveniences. The diesel could run only when the submarine surfaced (until the late introduction of the snorkel), the electric propulsion on battery only was quite short, and the speed was very limited. For example, the U-boat Type VII had an autonomy of around 20hrs @4kn and only 2.5hrs @6.8kn.

In recent years, the advancement in the science of batteries like the Li-ion ones allow submarines to stay underwater longer and give them better speed and they recharge faster; it's a big advantage, reducing the indiscretion time, which is the time when the boat needs to use its snorkel to run the diesel engines. During that time, the submarine generates more noise, and the mast can be detected by ASW assets, RADAR, or electro-optic systems.

The endurance of those submarines on batteries only is not publicly known, but estimations give a few days @ 5kn and 24hrs @10kn.

## AIP (AIR INDEPENDENT PROPULSION)

Air Independent Propulsion (AIP) refers to all the naval propulsion technologies that allow a non-nuclear submarine to operate without access to atmospheric oxygen. It sits between the traditional diesel/electric and nuclear propulsion.

There are **five main AIP technologies**; some have been improved over time, but there are new technologies tested in laboratories, and a few others are just concepts, and we will not elaborate on them, like the radioisotope thermoelectric generators (RTGs) cell, the Molten Carbonate Fuel Cells, or the Solid Oxide Fuel Cells (SOFCs).

Stirling engines, fuel cells, closed-cycle diesel engines, closed-cycle steam turbines (MESMA) and nuclear batteries.

Historically, the first application of AIP was made by the Germans during World War II, following the loss of numerous submarines in the Atlantic.

### ■ The Walter engine

Hellmuth Walter pioneered the technology, developing the Walter engine using High-Test Peroxide (HTP), also known as Perhydrol. It is a highly concentrated (85 to 98%) solution of hydrogen peroxide ( $H_2O_2$ ).

When in contact with silver or platinum (a catalyst), the HTP decomposes exothermically into steam and oxygen, producing a high-temperature gas (over 600°C). In the Walter turbine, which was a closed-cycle steam turbine, diesel fuel was injected. This resulted in an engine that could propel a submarine at more than 26 knots—13 knots faster than the speediest boats at the time.

This turbine was not without drawbacks; the HTP mixture is highly corrosive and necessitated special piping without any right angles (the component would “pile up” and, under pressure, this generally ended with an unintentional explosion).

After the end of the war, the Royal Navy experimented with HTP as an oxidizer in the experimental high-speed target/training submarines Explorer and Excalibur between 1958 and 1969. British experiments with HTP as a torpedo fuel were discontinued after a peroxide fire resulted in the loss of the submarine HMS Sidon (P259) in 1956. The Walter turbine was deemed too dangerous to be used, and the first AIP system was abandoned for submarine propulsion, but not for torpedoes. Russia uses HTP as a propellant for some of its torpedoes. On August 12, 2000, a Type 65 torpedo exploded on board and sank the Kursk (K-141) submarine.



Figure 22: The Kursk on the dock after the accident.

### ■ The Stirling engine

AIP was revived in the 1980s and 1990s by the Swedish with the Stirling engine, invented by Robert Stirling in 1816.

The Stirling engine is an external combustion engine operating on the Stirling thermodynamic cycle. Unlike internal combustion engines, the Stirling engine's working gas (typically helium or hydrogen) is sealed within the system and is alternately heated and cooled by external heat exchangers. In submarine applications, heat is generated by combusting diesel fuel with stored liquid oxygen (LOX) in a pressurized chamber. The resulting temperature differential drives pistons, producing mechanical work that is converted to electricity for propulsion or battery charging.

A key advantage of the Stirling engine is its ability to operate with virtually any fuel and its inherently quiet, low-vibration operation. The external combustion process, combined with the use of seawater as a heat sink, results in minimal acoustic and infrared signatures. The exhaust gases, primarily carbon dioxide and water vapor, are dissolved in seawater and expelled at depth, further reducing detectability.

The Swedish Navy pioneered operational Stirling AIP with the Näcken-class prototype in 1988, followed by the Gotland-class (commissioned 1996) and the upgraded Södermanland and Blekinge classes. Gotland-class submarines, equipped with two Kockums V4-275R Stirling engines (75 kW each), can remain submerged for up to two weeks at patrol speeds.

The Japan Maritime Self-Defense Force (JMSDF) adopted Stirling engines on their Sōryū-class submarines (commissioned 2009–2019), which feature four Kawasaki Kockums V4-275R Stirling engines. The Republic of Singapore Navy (RSN) Archer-class (ex-Swedish Västergötland-class) submarines were retrofitted with Stirling AIP modules (2x Kock-

ums V4-275R). The People's Liberation Army Navy (PLAN) has installed Stirling AIP in the Type 039A (Yuan-class) and Type 032 (Qing-class) submarines, reportedly based on Swedish technology.

The Stirling engine, like other AIP technologies, has unique advantages and inconveniences. It is very reliable because there are few moving parts. There is no explosion like in a diesel engine, so it is exceptionally quiet, and finally, this type of engine can use a wide variety of fuels.

But there are also some disadvantages beyond the physical size of the engine heat exchangers; the main ones are longer warm-up times and reduced responsiveness to speed or rapid load changes, since its operation depends on heat transfer through heat exchangers as we saw earlier.

### ■ The Fuel Cell AIP

Fuel cells are electrochemical devices that convert the chemical energy of a fuel (typically hydrogen) and an oxidant (oxygen) directly into electricity, with water and heat as the only byproducts. The most widely used fuel cell type in submarines is the Proton Exchange Membrane Fuel Cell (PEMFC), favored for its high efficiency, rapid start-up, and compact design.

In submarine AIP applications, hydrogen is stored either as a compressed gas, in metal hydride tanks, or generated on board via the reforming of hydrocarbons (e.g., ethanol or diesel). Oxygen is stored as LOX. The fuel cell stacks are typically arranged in modular units, each producing between 30 and 120 kW, and can be scaled to meet the vessel's power requirements. The electricity generated is used for propulsion and battery recharging.

### ■ Closed-Cycle Diesel Engines

Closed-cycle diesel engines (CCDE) are adaptations of conventional diesel engines that operate underwater by supplying oxygen (usually as LOX) mixed with recycled exhaust gases or inert gases (e.g., argon) to support combustion. The engine's exhaust is scrubbed of carbon dioxide and water vapor, with the remaining gases recycled or expelled overboard. This allows the diesel engine to run submerged, generating electricity for propulsion or battery charging without atmospheric air.

The Quebec-class (Project 615) submarines (1950s) featured three diesel engines, one of which could operate in closed-cycle mode using LOX. These boats suffered from significant safety issues, including several catastrophic explosions, earning the nickname "cigarette lighters." The technology was ultimately abandoned due to operational hazards and logistical challenges.

## ■ Closed-Cycle Steam Turbines (MESMA) and Ethanol-Oxygen Systems

The French MESMA (Module d'Énergie Sous-Marin Autonome) system is a closed-cycle steam turbine AIP technology. It operates by combusting ethanol (or other hydrocarbons) with LOX at high pressure (up to 60 atmospheres) to generate steam, which drives a conventional Rankine-cycle turbine. The exhaust carbon dioxide is expelled overboard at any depth thanks to the high system pressure, eliminating the need for compressors.

## NUCLEAR REACTOR

Nuclear reactors have been a reality since the end of 1942 with the Chicago Pile-1, and naval reactors debuted at sea in 1955 with the Nautilus (SSN-571) equipped with an S2W reactor—the first naval reactor. The S1W reactor was only used ashore for development and crew training.

The Soviets introduced their first nuclear submarine in 1958 with the K-3 Leninsky Kom-somol (Project 627), equipped with two VM-A 70 MW reactors. A few years later, the Royal Navy developed the HMS Dreadnought (S101) with the assistance of the US, which provided the S5W reactor. Very few other nations followed, such as France (1967), China (1970), and India (2016).

### ■ How does a naval nuclear reactor work?

A nuclear reactor uses the fission of uranium (or plutonium) to produce heat in a pressurized vessel where a coolant circulates. That coolant is contained in a primary circuit to avoid radioactive contamination of the other elements of the propulsion system.

The coolant, at around 320°C and under a pressure of 160 bar, transfers its heat into a heat exchanger for a secondary circuit, which feeds a steam turbine connected to an electric generator or a clutch/reducer connected to the propeller shaft.

Modern submarines tend to use electric motors for propulsion since it's easier to control the speed while keeping the reactor at the same power output.

Two models of the nuclear propulsion circuit:

- Primary circuit → Secondary circuit → Steam Generator → Clutch → Shaft → Propeller
- Primary circuit → Secondary circuit → Electric Generator → Electric Motor → Shaft → Propeller

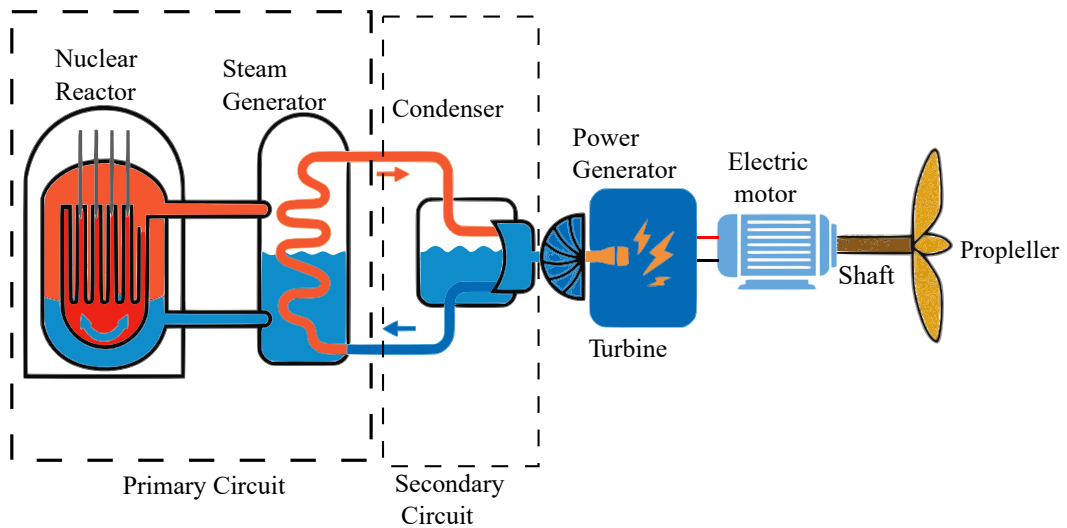


Figure 23: Simplified Nuclear reactor propulsion system.

There are two types of nuclear fuel currently used: HEU (Highly Enriched Uranium) and LEU (Low Enriched Uranium).

HEU refers to fuel enriched up to 95%; LEU is usually under the 20% threshold defined as civilian fuel by the Nuclear Suppliers Group meeting in London in 1975.

The USA and Russia (and both their allies) use HEU in their naval reactors; the main advantage of HEU is that you don't need to open the reactor to reload it with nuclear core fuel for the entire lifespan of the vessel, usually over 30 years.

On the other hand, LEU reactors need to be refueled every 8 to 10 years (the French use Uranium Oxide Ceramic), and the submarine reactor needs to be accessible from the outside of the hull for replenishment. The advantages of using LEU are that you don't need specialized enrichment and recycling factories, you can use civilian infrastructure, and there is no international restriction on exporting nuclear fuel under international laws.

## ■ Coolants

For cooling the reactor, the easiest way is by using pressurized water. This is the norm, but since the invention of nuclear propulsion, a few other coolants have been tested, like bismuth/lead or sodium. In the end, water became the coolant of choice due to its thermal conductivity and ease of use. The nonconventional coolants needed to be heated all the time, or they would solidify in the circuit, rendering it nonoperational. This required extra infrastructure near the submarine berths.

In the previous sections, we went through some of the main elements of a modern submarine. In the next section, we will cover noise reduction.

## NOISE REDUCTION

Submarine self-generated noise is one of the main concerns when developing a new submarine.

Since the 1960s and the Albacore experiment, new techniques have been developed to reduce the sound signature of submarines. Here are a few examples:

1. High-precision manufacturing of equipment like the propeller and shaft. The goal is to reduce imbalance and friction between parts, lowering vibrations.
2. Isolation of all noisy machinery from the hull using dampeners.



Figure 24: Example of an industrial shock dampener.

3. Using rafting and double dampening: equipment is mounted on a harmonic balancer, and the rafts are also isolated from the hull using shock absorbers.
4. SHT (Special Hull Treatment) and Anechoic coatings/tiles

Special Hull Treatment is a term used to describe all the methods and processes used to reduce noise and the proliferation of slime on a submarine's external hull. It can be attained by using special paints and/or applying tiles to the hull.

If a hull is left without protection, the growth of microorganisms affects the performance of the boat by creating unwanted water flow disturbances and noise. Antifouling paints are used to prevent or slow the proliferation of slime (biological organisms). The most common deterrent used is copper and its oxide derivatives. Copper is a well-known biocide. Today, the trend is to use other chemicals since copper has a negative impact on the normal development of marine fauna.

Anechoic coatings/tiles are often used on the hull to reduce self-noise and echoes from enemy active SONAR. These tiles are made of different types of polymer or rubber that include tiny voids (like very small bubbles). Those tiles are glued to the hull, but due to environmental constraints (temperature, pressure, etc.), we often see them missing when a submarine goes back to port.

A new technique called Mold-In-Place is used on Virginia-class submarines. It consists of adding the tiles by molding them directly onto the hull. This process requires a special drydock with a temperature and humidity-controlled environment.



Figure 25: Missing tiles on a Virginia submarine (Creator: MC2 Jonathan Sunderman | Credit: U.S. Navy)

As you saw, a submarine is a very complex system, and we have literally just scratched the surface. For those with an interest in submarine design, we have provided a few references at the end of this chapter.

In the simulator, you will not roam freely through the submarine; your working space/office is the Combat Information Center. This part is just a very brief introduction to the tools

you will find. There will be an in-depth chapter on the use of the different stations in the operations manual.

## COMMAND AND CONTROL CENTER

The Combat Information Center (CIC), or now the Command and Control Center (CaCC), is the central place where situational awareness, decisions, orders, and finally, executions are made; consider it as the head of the submarine with ears (SONAR, RADIO, ESM), a mouth (RADIO), eyes (PERISCOPE), and a brain (CO/XO/Crew).

To make a decision, the CO / XO needs to have:

- A clear picture of the outside environment – DATA COLLECTION
- A way to display it and devise tactics – TACTICAL DECISION
- A way to coordinate and communicate with the exterior world – COORDINATION and COMMUNICATION
- A way to guide the boat exactly where they want and control the weapons available - EXECUTION SIDE

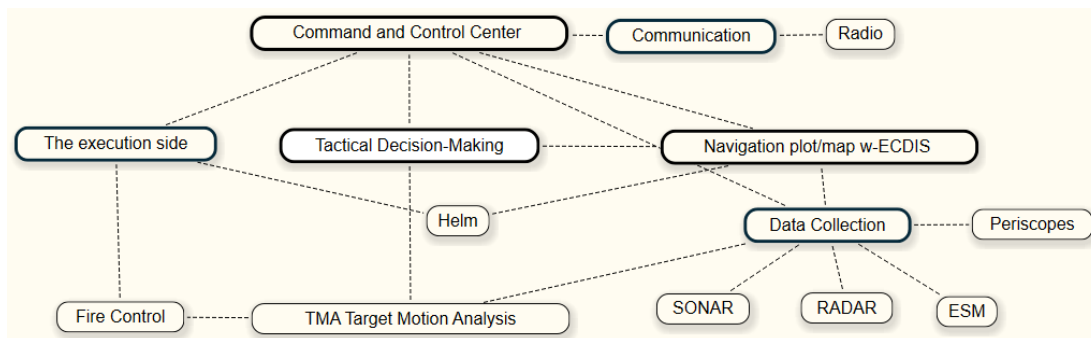


Figure 26: The decision-making graph.

## DATA COLLECTION

This refers to the entire apparatus used to (re)create the best picture of the external world underwater and on the surface (and above). For this, the Captain and the CIC crew have four main ways to achieve this goal:

- SONAR
- Periscopes
- ESM
- RADAR

### ■ SONAR (Sound Navigation And Ranging)

SONAR uses the propagation of sound underwater to detect, identify, and classify “contacts” and get a rough estimate of their depth, range, and bearing; those can be biological entities, civilian or military ships, and other submarines.

A submarine usually has several SONAR sensors aboard; the main one is located in the bow (it can be cylindrical, spherical, or horseshoe-shaped). Since the 1960s, boats can also carry a Towed Array, a set of transducers at the end of a lengthy cable (between 500-1000m), and more recently, modern submarines have received flank arrays on the sides of the hull, like the LWAA of the Virginia class.

They are also equipped with other SONAR units like a Fathometer to get the depth below the keel, or specialized sonar to detect mines, ice, or obstacles in front of the submarine. Those types of SONAR are active, which means they emit sound and receive echoes.

SONAR stations on submarines are divided mainly into Broadband and Narrowband, but there are also some other sub-functions like LOFAR, DEMON, and Environment.

### ■ Periscopes, photonics, and optronics

Modern submarines, like their predecessors, usually host two periscopes. From WW2 to the end of the Cold War, there was one observation and one attack periscope. The observation one had a wider field of view, and the attack one was slimmer and harder to detect.



Figure 27: Modern photonic periscope head.

The trend today is to use optronic (or photonic) masts, which use digital cameras (visible, day/night, and infrared) and laser range finders. The main advantage is that there is no more hull penetration or physical wells extending through the CIC down to the lower decks. This allows submarine designers to construct new configurations for the CIC. Modern submarines use optronic periscopes much like their predecessors hosted two; one reason is for redundancy since electronics, even military ones, can break down, and fixing a periscope while surfaced or underwater is not an option during a mission. The second reason is to feature different sensors, elevations, fields of view, etc.

## ■ ESM (Electronic Support Measures)

This station is used for the interception, analysis, classification, and identification of all radio emissions in the range of the submarine. ESM refers to the components—all the electronics, antennas, recorders, and computers—used for ELINT.

Usually, submarines have one dedicated ESM mast with all the different receivers, but also a smaller one on the top of the periscope. This latter one is mainly used when raising the periscope to alert the crew of an imminent danger of being detected by a ship or an anti-submarine airborne asset.

ESM collects different types of Electronic Intelligence (ELINT), for example:

- **COMINT:** Communication Intelligence, collected by listening to radio communications. Sometimes they can be translated by linguists from intelligence agencies embedded aboard the submarine. Mapping the volume of activity can help determine where command centers are located.
- **SIGINT:** Signal Intelligence, collected by analyzing RADAR emissions (frequency, pulse duration, strength, etc.) and comparing them to a signature database to determine what type of radar is being used.
- **TELINT:** Telemetry Intelligence, collected by intercepting telemetry data from missile tests. Recording these data and later decrypting them in land-based labs helps intelligence agencies assess enemy system capabilities.

All data recorded by the ESM are analyzed further when the submarine returns to port by different specialists and agencies.

## ■ RADAR

Submarines use RADAR only when surfaced for safety and collision avoidance, though it can also be used for searching. Modern units, like the AN/BPS-16(V4) on the Virginia class, work in the I-band using frequency hopping to achieve a Low Probability of Interception (LPI) of the signal.

## COORDINATION AND COMMUNICATION

## ■ Radio

Submarines use a wide range of radios and frequencies from Extremely Low Frequency (ELF) to Ultra High Frequency (UHF) and SATCOM. Each of these frequencies has its own advantages and disadvantages.

Band	Depth Penetration	Range	Data Rate	Direction	Practical Use
ELF - Below 3 Hz	Deep	Global	Very low	Reception Only	Signaling submerged submarines to surface
VLF - 3 kHz to 30 kHz	Shallow	Long-range	Very low	Reception Only	Signaling submerged submarines to surface
HF - 3 MHz to 30 MHz	Surface	Medium	Medium to High	Bi-directional	Communication when near the surface
UHF - 300 MHz to 3 GHz	Surface	line-of-sight	High	Bi-directional	Fast data transfer, periscope-depth comms
UHF SATCOM - 240-270 MHz	Surface/PD	Global	Moderate	Bi-directional	Encrypted voice/data, situational updates
SHF SATCOM - Ku-band	Surface/PD	Global	High	Bi-directional	High-data applications (video, tactical data)
EHF SATCOM - Ka-band	Surface/PD	Global	Very High	Bi-directional	Secure, anti-jam communications

Table 1: Different types of communications systems used by submarines.

## TACTICAL DECISION-MAKING

Decisions are made using all the data above and combined into two different systems: one used for navigation and tactical display, and the other to compute the course and distance of targets using data from the SONAR suite.

### ■ Navigation plot/map

W-ECDIS - Warship Electronic Chart Display and Information System. This mapping screen/table can display charts, depth, and other vessels' positions using AIS, radar, receive/send text messages, plot courses, determine positions using GPS/INS, and a lot more.

### ■ TMA Target Motion Analysis

This station is in charge of determining the range, bearing, course, and speed of a contact using data from the SONAR or the RADAR. The results can then be used by the Fire Control station to assign a weapon to hostile targets.

## THE EXECUTION SIDE

## ■ Helm

This station controls the speed, course, depth, and trimming of the boat. They receive their orders from the Officer of the Deck (OOD).

Usually, three crew members are assigned to the helm, but in newer submarines with computerized fly-by-wire controls, a single helmsman can “drive” the boat. This station is also responsible for deploying/retrieving the masts, wired antennas, and towed array sonar.

## ■ Fire Control

This station assigns weapons to tracks (targets) and enters all the necessary parameters to guide them (waypoints, depth/altitude, attack mode, etc.). These can be torpedoes, anti-ship missiles (Harpoon), or cruise missiles (Tomahawk) against land targets. In this case, flight parameters are directly entered into the computer when mission orders are given to the submarine.



Figure 28: View of a Virginia-class CaCC.

## THE CREW

A submarine is nothing without a crew; these men and women are doing a highly technical job in a dangerous environment.

The commanding structure varies from navy to navy but usually follows the one listed below.

The wardroom is composed of the top-tier commanding and executive officers (CO, XO, and division officers):

- The Commanding Officer (CO) is the officer in charge of the submarine; he has authority over every aspect of the boat's operations, and he is the one who makes all final decisions regarding navigation, combat, engineering, safety, and mission execution.
- The Executive Officer (XO) manages the submarine's daily operations, discipline, and administration, ensuring the CO's orders are executed.

There are usually four officers under the CO and XO, each commanding one Division:

1. Engineer Officer ("Eng") is in charge of the nuclear reactor, the propulsion plant, and all basic mechanical and electrical systems.
2. Navigator ("Nav"), as the name suggests, takes care of the boat's navigation but is also responsible for the communication systems (radio, satellite, etc.).
3. Weapons Officer ("Weps") oversees the Weapons department. He manages the crew handling the sonar systems, Fire Control, and is responsible for the maintenance of all weapons and countermeasures aboard.
4. Supply Officer ("Suppo" or "Chop") handles logistics, from food to the spare parts needed for the mission. He also has an administrative role aboard the submarine and supervises the Culinary Specialists (Cooks).

So, here is the end of this very short introduction to submarine history and the complexity of modern submarines. We hope you learned a little. To complete this text, we added a bibliography at the end with some must-read books if you really want to dive deeper (all pun intended) into these fascinating subjects. We acknowledge there are certainly some mistakes, but the goal was to create a text everyone can understand, from a teen who dreams of becoming a submariner one day to a future CO of their own submarine.



# A SHORT INTRODUCTION TO THE OCEANS AND SOUND PROPAGATION

## INTRODUCTION

Why a chapter exclusively dedicated to the theory of sound propagation?

The answer is simple: you can't fight in this environment if you don't have a clear understanding of how sound propagates in seawater. You can hide, detect, and finally successfully execute your mission using the ocean to your advantage, but first you need to understand some basic concepts.

The global ocean is not an acoustically uniform medium. Its behavior is governed by the interaction of geography, geology, chemistry, physics, meteorology, and oceanography. These domains combine to create a dynamic environment where sound bends, reflects, scatters, attenuates, and sometimes travels halfway across the globe.

This chapter provides a structured and, we hope, an accessible introduction to ocean acoustics. We tried to use clear language, far from scientific lingo and figures. Yes, there are a few equations, but only those necessary to fully understand underwater acoustics, and we tried to explain them with examples and applications.

A separate bibliography is available at the end of this chapter for the nerds who want to dive deeper into the subject (pun totally intended). Finally, a glossary of unfamiliar terms used in this text is available for your reference.

Modern Naval Warfare was built from the bottom up, starting with the container (the bathymetry and the seabed structure), adding the medium (the seawater) with its physical properties, then the physical models related to underwater sound propagation.

This chapter will follow this logic, starting with the first part: the ocean environment, its physical properties, and the vertical structure of the water column. Following this, we will introduce the fundamentals of sound, including its speed and profile underwater. The third part will introduce Fermat's principle, Snell's law, and ray theory; sound paths related to sound speed and sound loss in seawater. The next part will focus on ambient noise, the particularities of shallow water, and, finally, why sound is better than RADAR radio frequencies or LASER.

## THE CONTAINER: THE BATHYMETRY AND SEABED

Seventy point eight (70.8) percent of the surface of Earth is covered by water (in liquid or solid form). Almost 66% of the world's population lives within 150 km of the coast, commercial trade is handled by maritime shipping, which accounts for 80% of the total value of goods transported, and this number might jump to 85% in the next five years. Oceans are also a source of food, oil and gas (via offshore drilling), and, in the future, the “mining” of polymetallic nodules from the seabed.

All those numbers and facts show the critical strategic value of the oceans and seas.

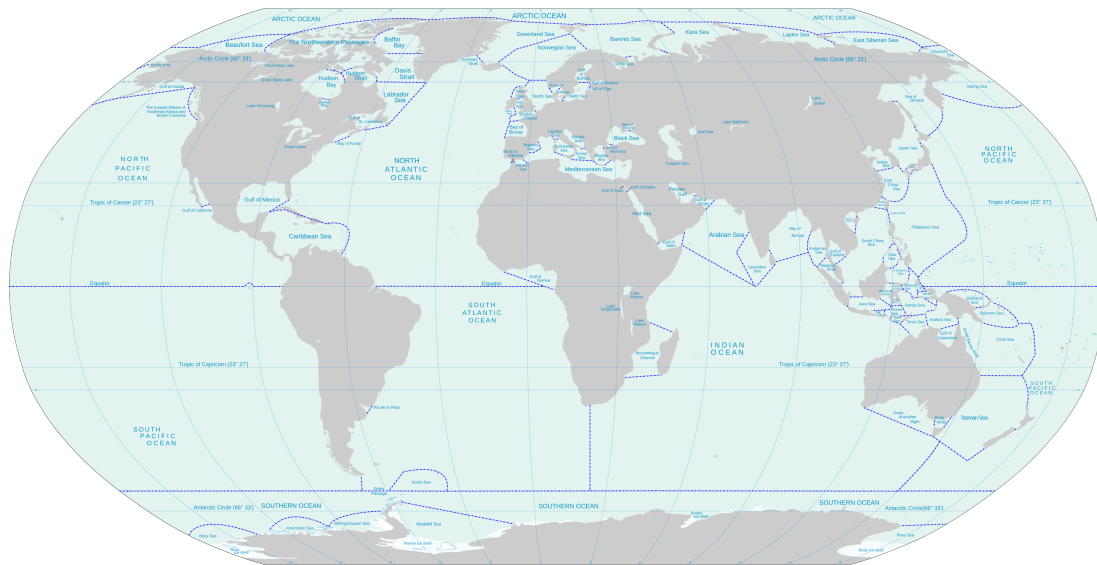


Figure 29: Oceans and Seas of the world.

There are five oceans: Atlantic, Pacific, Indian, Arctic, and finally Southern; and nine main seas (Mediterranean, Baltic, North, Black, Caspian, Red, Arabian, Caribbean, and South China).

Most of the seas are subdivided into regional seas; e.g., the Mediterranean Sea comprises the Aegean Sea, the Alboran Sea, the Ionian Sea... We often refer to oceans and seas, but what is the difference between the two?

The distinction between oceans and seas lies in their geographic characteristics. Seas are typically partially enclosed by landmasses—either continents or island chains—while oceans are vast, open bodies of water. The Sargasso Sea presents a unique exception, defined by circulating ocean currents rather than physical boundaries.

## SEABED TOPOGRAPHY

The topography of the bottom of the oceans and seas is not flat; like on the surface, there are mountains, valleys, cliffs, ridges, etc. (fig. 30). Those reliefs are the result of tectonic plate movements, volcanic activity, and finally erosion and sedimentation.

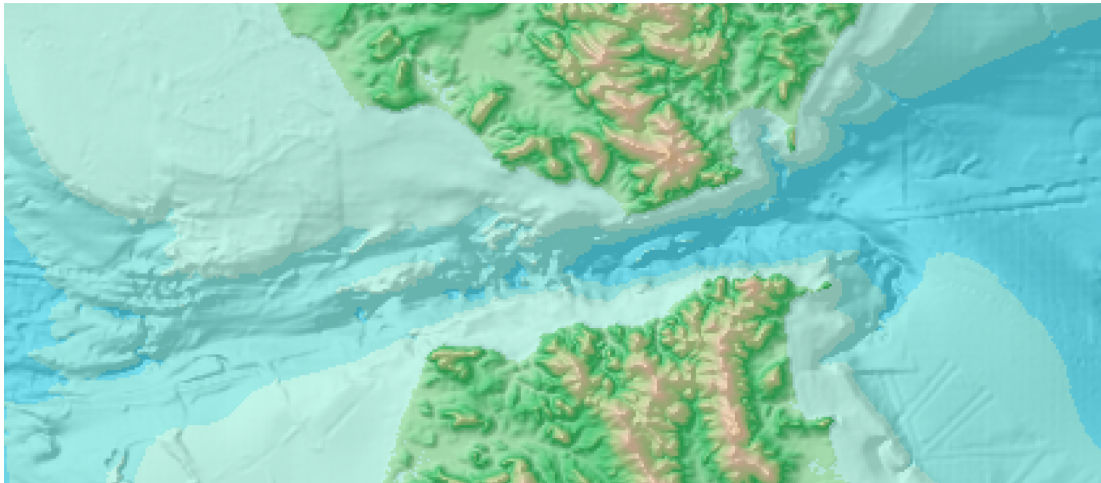


Figure 30: Topography of the Strait of Gibraltar.

Tectonic activity:

- When plates are moving away from each other, known as “divergent boundaries” or extensional boundaries, it results in the creation of mid-ocean ridges (like the well-known Mid-Atlantic Ridge).
- When one plate subducts beneath another, known as “convergent boundaries”, it creates trenches. The most famous is the Mariana Trench, the deepest measured so far on Earth at -10,984 m. A trench can be filled completely or partially with sediment.

Regarding volcanic activity, you should note that tectonic and volcanic activities are related.

Volcanoes create seamounts (volcanoes that didn’t reach the surface) or volcanic islands—some isolated like Krakatoa, some forming a chain of islands as the plate moves away. The most famous is the Hawaii archipelago, a chain of 137 volcanic islands in the mid-Pacific (fig. 31).

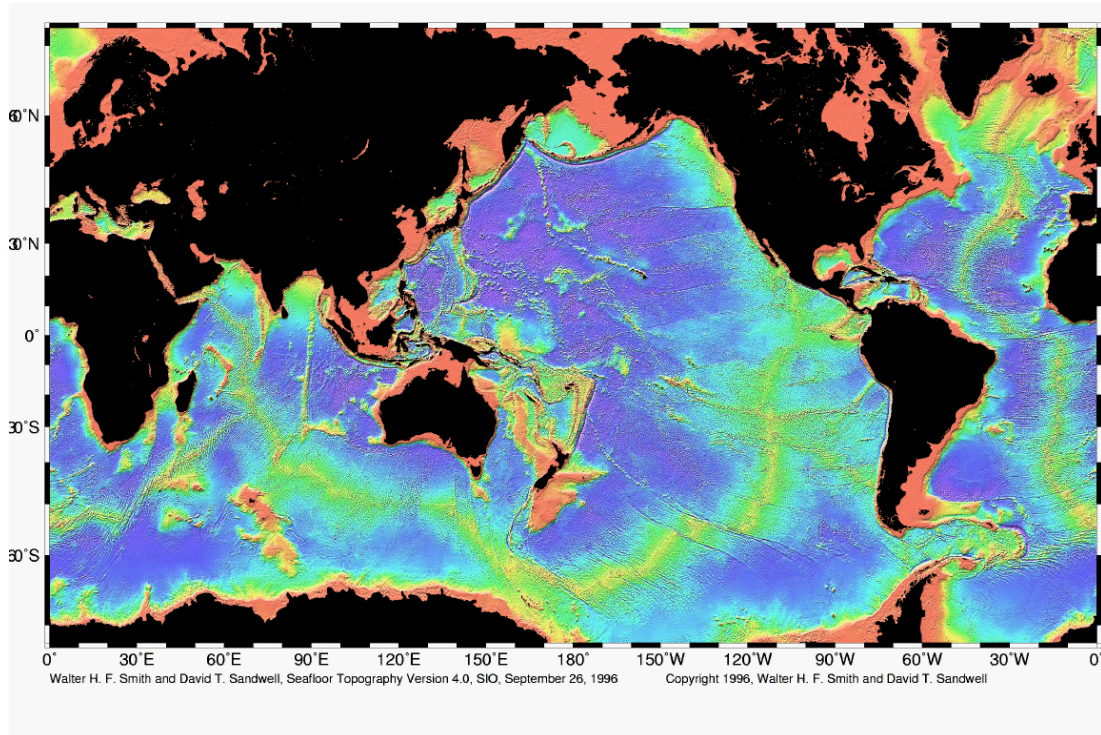


Figure 31: Seabed topography.

Last but not least, there is erosion and sedimentation (fig. 32).

There are three main origins of sediment: biogenous, terrigenous (or orogenic), and finally hydrogenous.

1. **Terrigenous sediments** are deposits derived from the erosion, weathering, and transport of materials from continental landmasses, carried primarily by rivers, wind, glaciers, and gravity into marine environments. These sediments are typically rich in silicate minerals such as quartz and clays and dominate nearshore and continental shelf regions, forming a significant portion of oceanic sediment.
2. **Biogenous sediments** are formed from the accumulation of organic material derived from the remains of marine organisms, from the tiniest ones to dead whales. These sediments primarily consist of calcium carbonate or silica. Biogenous sediment is found extensively in pelagic (deep-sea) environments.
3. **Hydrogenous and authigenic sediments** are seabed materials that form directly from dissolved substances in seawater or porewater, rather than being transported from land or produced by biological remains.

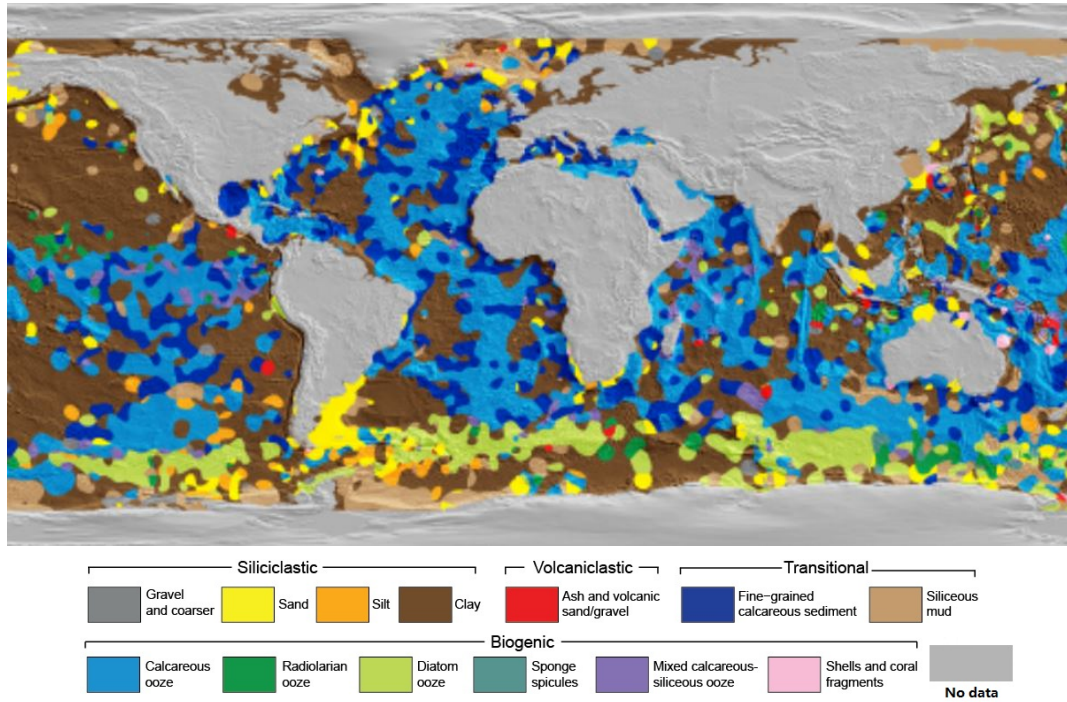


Figure 32: Sediment distribution by type.

The thickness of those sediments ranges from a few millimeters to over 10 km near rivers such as the Mississippi, the Amazon, and the Ganges, for example (fig. 33).

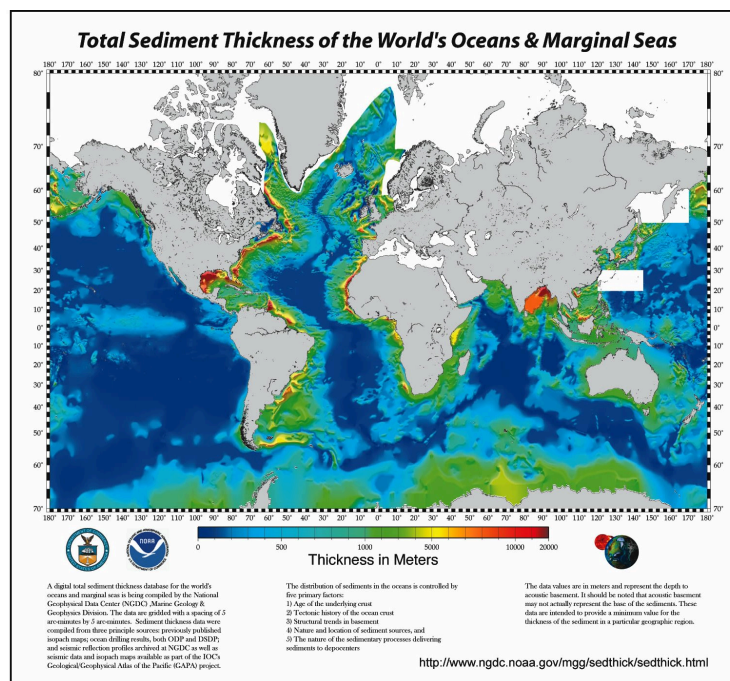


Figure 33: Sediment thickness.

The ocean floor is complex, and this intricacy will, under certain conditions, affect how underwater sound interacts with this interface. Sound can be absorbed, scattered, dif-

fused, or reflected upward when reaching the seafloor, depending on factors that we will introduce later on.

These geological and sedimentary structures form the acoustic bottom boundary, influencing reflection, scattering, and absorption.

But sound requires a medium to propagate, so we now examine the physical properties of seawater itself.

## THE MEDIUM: SEAWATER (PHYSICAL AND CHEMICAL PROPERTIES)

We now turn to the ocean, not to swim in it, but to examine its composition and physical properties. Those are very important to understand how sound propagates. Two of the main characteristics are temperature and salinity, but a few others are also important in the study of acoustics in seawater, such as pressure and pH, for example.

### TEMPERATURE

The mean ocean temperature varies from +32 °C at the surface down to -1.8 °C (below the freezing point of pure water) at greater depths.

The sea temperature doesn't usually exceed 32.5 °C due to a negative feedback loop (when the surface gets hot, there is more evaporation and convection of humid air; when it reaches cold air at altitude, it condenses and forms clouds which block the sun and therefore the heating of the surface). But locally, the temperature can reach up to 38–40 °C, for example, in the Red Sea.

The Sea Surface Temperature (SST) is the temperature of the uppermost layer of the ocean, typically measured in the top 1–5 meters. It represents the thermal state of the ocean–atmosphere interface (fig. 34). From this figure, some global spatial patterns are evident. The warmer waters are found in the tropical western Pacific and Indian Ocean; on the other hand, the cooler waters are toward the poles, approaching 0 °C in high latitudes.

Eastern boundary currents (like those around California or the Canaries) show cool upwelling zones; on the contrary, Western boundary currents (like the Gulf Stream or Kuroshio) show warmer and fast-flowing currents.

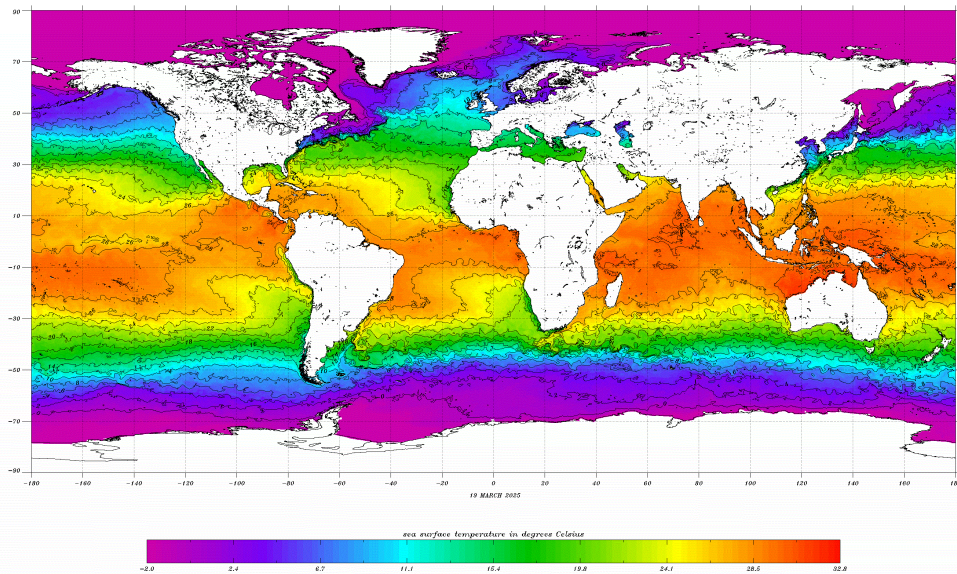


Figure 34: Global mean Sea Surface Temperature (SST).

Temperature is the dominant factor affecting sound speed in the upper 1000 m of the ocean.

The second most important factor affecting sound propagation is salinity. We all know that seawater is salty, but why? From where does the salt originate, and is the concentration the same spatially?

## SALINITY

Ocean salts originate from two main sources: land runoff and seafloor vents.

Land runoff is the primary contributor. Rainwater, slightly acidic, erodes rocks, releasing ions that are carried by rivers into the ocean. Some of these ions are used by marine organisms, while others accumulate over time.

The second source is hydrothermal fluids (mineral-rich waters that originate from beneath the Earth's crust) from seafloor vents. Seawater seeps into cracks in the ocean floor, where it is heated by magma. This process causes chemical reactions that enrich the water with metals like iron, zinc, and copper. Volcanic eruptions also release minerals into the ocean.

Salt domes, large deposits of salt formed over geological periods, further contribute to ocean salinity. These are found underground and undersea, particularly around the northwestern Gulf of Mexico.

In seawater, chloride (Cl) and sodium (Na) are the most abundant ions, making up about 85% of the total. Magnesium and sulfate account for another 10%, with other ions present in smaller amounts. Salinity, the concentration of salt in seawater, averages about 35 parts per thousand, or 3.5% by weight. It varies with temperature, evaporation, and precipitation, being lower at the poles and equator and higher at mid-latitudes.

Ocean salinity is variable in time and space (Fig. 35). Regions with high evaporation and little freshwater input show higher salt concentrations (mainly in tropical areas); by contrast, areas with heavy rainfall (like Southeast Asia) or with river runoff (like the Ganges into the Bay of Bengal) have lower salinity. In high-latitude regions, cloud cover is higher (+70% of the time), water is colder, evaporation is lower, and rainfall is more pronounced. Table 2 summarizes the mean salinity of different oceans and seas. The spatial variability is significant, from 8 to almost 40 ppt (parts per thousand).

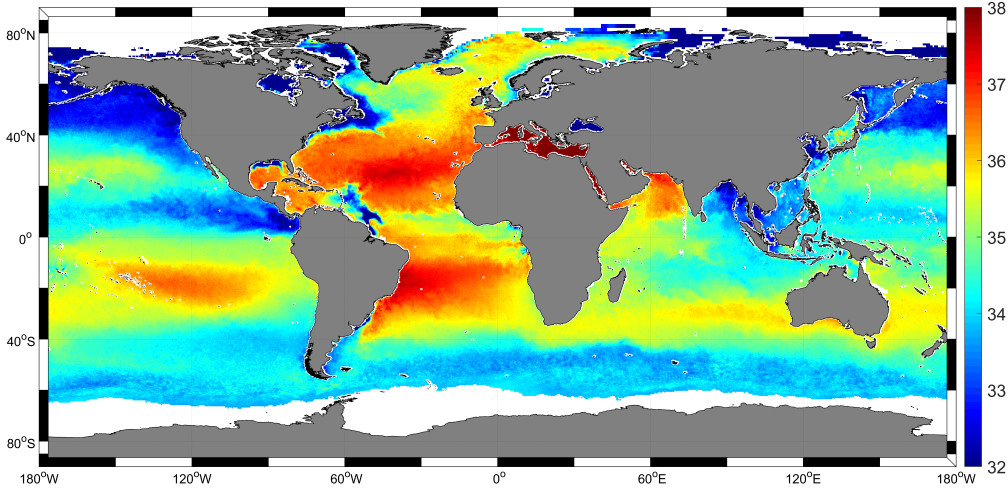


Figure 35: Horizontal distribution of the surface salinity.

Sea / Ocean	Salinity (ppt)
Baltic Sea	8
Black Sea	18
Mediterranean Sea	38
Red Sea	39
Indian Ocean	35
Atlantic Ocean	35-37
Pacific Ocean	31-37
Arctic Ocean	30-34

Table 2: Mean salinity in different Seas and Oceans.

**■ Pressure**

The third main characteristic important for the study of sound propagation is pressure. Well, it's more complicated; in fact, it is density, since pressure takes into account only the “weight” of the water above without taking into account the salinity and the temperature.

So, what is pressure?

Ocean pressure increases at a constant rate with depth. At the surface, the pressure is 1 atmosphere (1013 mb, 1 bar, or 14.696 psi). As depth increases, pressure rises by approximately 1 atm for every 10 m (or 33 feet). So at -10 m, the pressure is 2 atm or 29.26 psi, and at -50 m, it's 6 atm or 85.8 psi.

## ■ Density

Density ( $\rho$ ) is the ratio between mass and volume; it's expressed in  $\text{kg/m}^3$  or  $\text{lb/ft}^3$ .

$$\rho = \frac{m}{V}$$

Where: -  $m$  = mass, units typically [g] or [lb] -  $V$  = volume, units typically [ $\text{cm}^3$ ] or [ $\text{ft}^3$ ]

The density of pure water is  $1 \text{ g/cm}^3$  at  $3.98 \text{ }^\circ\text{C}$  ( $39.2 \text{ }^\circ\text{F}$ ), which means 1 cubic meter of water weighs 1000 kg.

The density of seawater ( $\rho$ ) varies slightly with temperature ( $T$ ) and salinity ( $S$ ) because  $T$  and  $S$  are not constant over time and across space (lat/long). Here is a simple approximation with a precision of 0.1% of the density:

$$\rho = 999.1 + 0.77 \cdot S \cdot \left( \frac{T - 15}{5.13} \right) - \frac{(T - 15)^2}{128}$$

The density of pure water depends only on temperature, but seawater is not pure. There is salt, which increases the water's density.

Since temperature has the most significant effect on density, density profiles are usually mirror images of temperature profiles. Density is lowest at the surface, where the water is the warmest. As depth increases, a region of rapidly increasing density forms, called the pycnocline. The pycnocline coincides with the thermocline, as the sudden decrease in temperature leads to an increase in density. Below the pycnocline, density may be relatively constant (as is temperature), or it may continue to increase slightly towards the bottom.

All three physico-chemical properties of seawater induce a layering of strata of the "same" type of water (salinity, temperature, and pressure). This results in a series of layers that will be important in how sound propagates in the sea.

## ■ Vertical structure of the water column

The ocean's structure is not uniform; there are variabilities in temperature ( $T$ ), salinity ( $S$ ), and pressure ( $P$ ) in space and time. The combination of those three physical characteristics creates a layering that can be quasi-permanent, seasonal, or transient (with a duration ranging from a few hours to a few weeks).

The layering of the oceans can be very complex, and depending on the science involved, the number of layers can be substantial, with layer depths ranging from 10 microns to hundreds of meters. Fortunately, oceanographic acoustics involves relatively few layers. Let's examine the vertical stratification of the ocean, starting from the top and proceeding downward.

## TEMPERATURE LAYERING

The temperature of seawater is not uniform throughout the column; it can vary daily and seasonally. You may have heard about the thermocline if you've ever read a book, seen a movie, or played a game involving a submarine, but that's not the only one.

### ■ Surface layer/mixing layer

As its name suggests, it's the uppermost part of the ocean, with a depth varying from a few meters down to 100 m. The action of currents and waves mixes the water, so the temperature and salinity across this stratum are uniform. See the following figure.

### ■ Transient layer

Transient layers are, by definition, layers that are not permanent; they change or disappear over time. There are mainly two: the diurnal and the seasonal.

The diurnal one (fig. 36) is the result of the daily heating of a small layer of the ocean (usually down to 10–15 m) *on a calm and windless day*. It tends to disappear overnight.

As for sound propagation, this type of temporary layer can affect the sonar reception of ships during times of higher sea temperature.

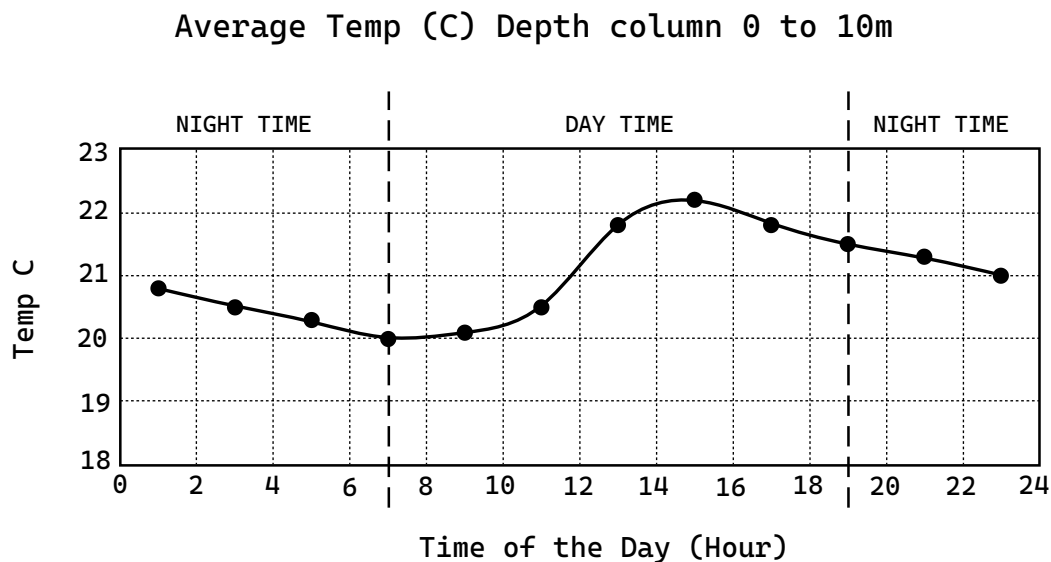


Figure 36: Daily variation of the SST (0-10m) in calm conditions.

### *The seasonal one*

Seasonal layers appear mainly during the summer when the sun warms the surface layer; the depth of this layer is greater than the diurnal layer, down to 50 m. The next figure shows that the temperature variability is greater during the summer months (July to September) than during the winter months (November to March).

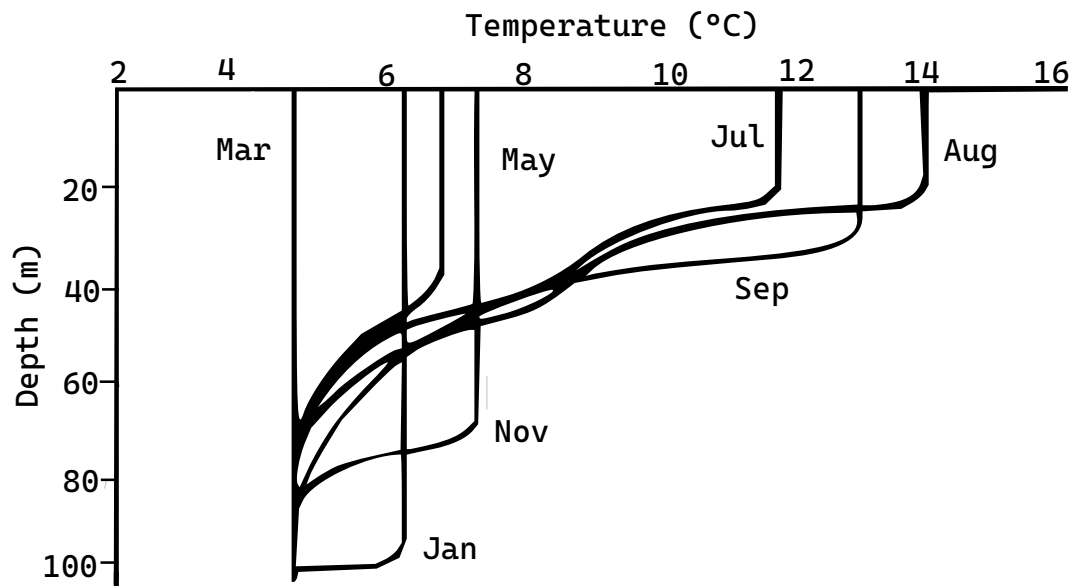


Figure 37: Seasonal layer.

The following figure shows the two other important layers: the thermocline and the isothermal deep water.

**Thermocline** The thermocline is a layer in the ocean where temperature decreases rapidly with depth, marking the transition between the warm surface layer and the colder deep waters.

**Isothermal deep water** This layer refers to the ocean's deep layers where temperature remains nearly constant with increasing depth, typically between 0 and +3 °C and unaffected by surface variations.

Diving “below the layer” refers to the thermocline. It is used to hide from detection by surface ships or shallow sonobuoys, but not other submarines in the same layer, variable depth sonar towed by ships, dipped sonars from a helicopter, or deep sonobuoys.

Temperature is not the only property that creates layers; salinity and consequently density have layers as well—respectively the halocline for salinity and the pycnocline for density. Usually, the thermocline and halocline are located at approximately the same depth: the lower limit of the mixing layer.

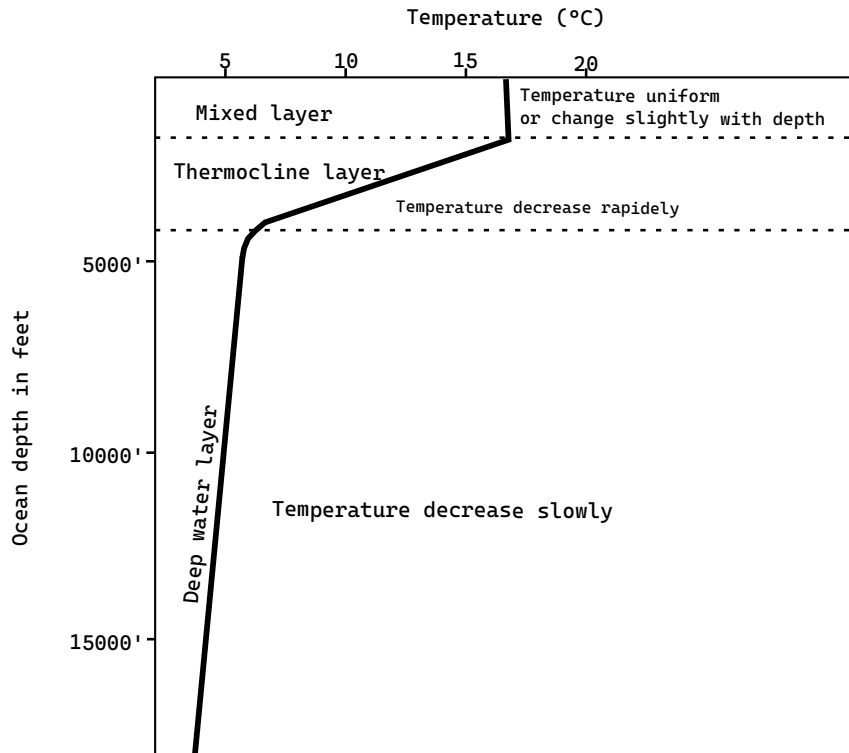


Figure 38: The most prominent layers of the ocean.

This figure shows the halocline for low latitudes and the pycnocline for both low and high latitudes. It is interesting to look at the pycnocline graphic. The density of the water varies more in low latitudes, near the equator, since the temperature changes are more pronounced there.

After introducing the container (bathymetry and seabed composition) and the fluid (sea-water) characteristics and variability, it's time to turn to the main subject of this chapter: how sound behaves in this complex environment. But before diving (pun intended) into that complex but manageable topic, let's define sound.

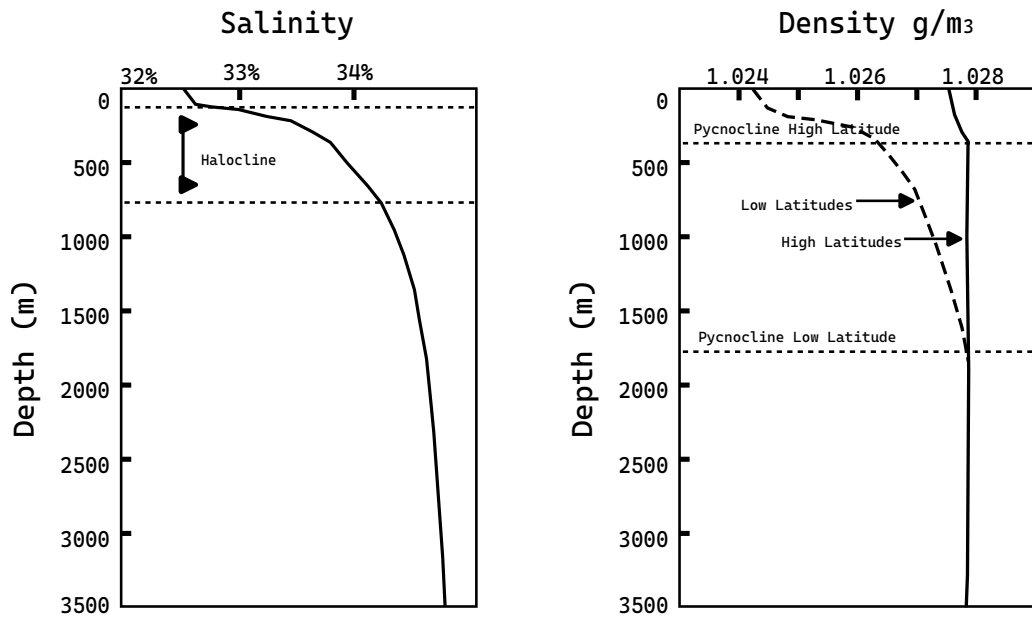


Figure 39: Halocline and Pycnocline.

## SOUND UNDERWATER

### WHAT IS SOUND?

In physics, sound is a type of mechanical wave that travels through a medium, such as air, water, or solids. It is produced by the vibration of objects, which creates pressure waves that propagate through the medium. These pressure waves consist of alternating compressions (where the particles are close together) and rarefactions (where the particles are spread apart).

### HOW DOES IT WORK?

Sound needs four components to close the loop from emission to reception:

1. **Source of Vibration:** Sound begins with a vibrating object, such as a guitar string or vocal cords, and in the case of the sea, an engine or rotating machinery, a hull slicing through the water, or biologics singing.
2. **Medium:** The vibration causes the surrounding medium (like air or water) to compress and expand, creating a wave.
3. **Transmission:** The sound wave travels through the medium from the source to the listener.
4. **Detection:** When the sound wave reaches a listener's ear, it causes the eardrum to vibrate, which the brain interprets as sound. In our case, it will be the transducers of the SONAR array.

Submarines and ships generate a variety of noises and frequencies, including:

- **Engine and Propeller Noise:** Typically in the range of 10 Hz to several kHz.
- **Hydraulic Systems:** Often emit noise in the range of 1 kHz to 10 kHz.

- **Cooling Systems:** Produce frequencies from around 100 Hz to a few kHz.
- **Water Flow and Cavitation:** These can produce sounds from 1 kHz to several tens of kHz, depending on the speed and conditions.

Note that sound needs a medium to travel through and cannot propagate through a vacuum. Yes, “In space, no one can hear you scream.”

Sounds are defined by three characteristics: frequency, amplitude, and velocity:

- **Frequency:** Determines the pitch of the sound; higher frequency means a higher pitch.
- **Amplitude:** Relates to loudness; larger amplitude means a louder sound.
- **Velocity:** The speed at which sound travels through the medium, which depends on factors like temperature and the medium’s properties.

The wavelength or period of a signal is the distance in cm or meters between two adjacent crests.

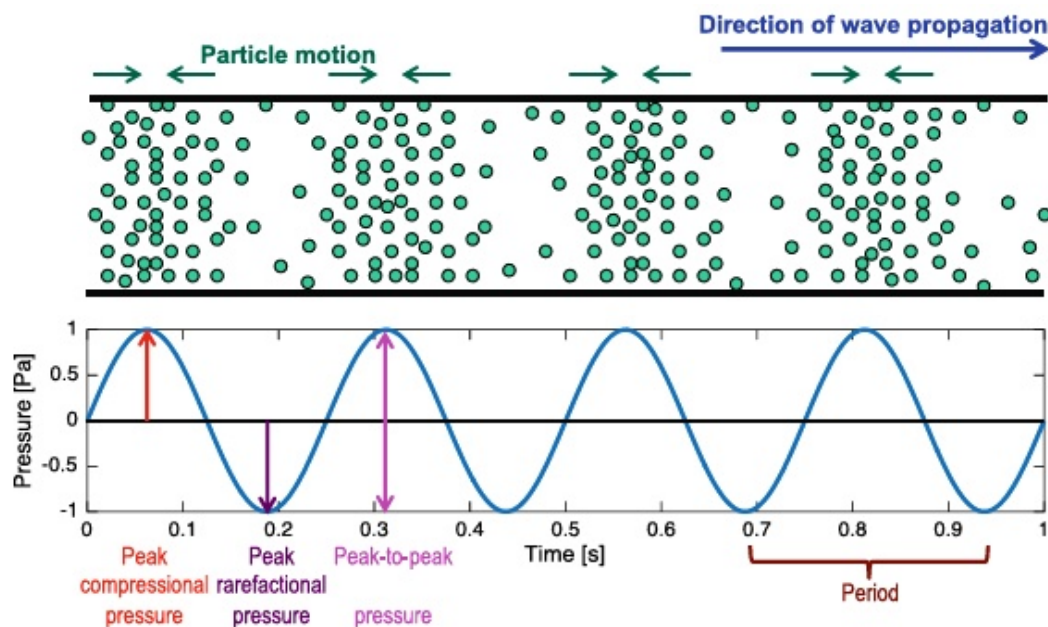


Figure 40: Sound theory, pressure, period, wavelength.

The denser the medium it travels through, the faster sound will travel.

For example, here (table 3) are a few sound speeds in different media.

Medium	Density (kg/m <sup>3</sup> )	Sound Speed (m/s)
Air	1.225	343
Water	1000	1482
Steel	7850	5960
Wood	600–800	3300
Glass	2500	5000

Table 3: Density and sound speed of different materials.

## WHAT IS A DECIBEL (DB)?

The decibel is 1/10 of a Bel, which is a logarithmic unit of a power or energy ratio like sound intensity or sound pressure. By definition, the decibel (dB) corresponds to 10 times the base-10 logarithm of the ratio. A dB has no unit since it is a ratio.

The decibel formula for sound pressure level **in air** is given by:

$$\text{dB} = 20 \times \log_{10} \left( \frac{P}{20 \mu\text{Pa}} \right)$$

Where  $P$  is the measured pressure and  $20 \mu\text{Pa}$  is the reference pressure for sound in air.

## DECIBEL IN AIR AND IN WATER

We can't directly compare dB values in air and seawater because the pressure reference is different: **20  $\mu\text{Pa}$**  for air (the reference pressure for air corresponds to the human hearing threshold at 1 kHz), while for water it's **1  $\mu\text{Pa}$** .

So, the baseline difference in dB due to the reference level between air and water is 26 dB. The 26 dB conversion factor is derived from the higher reference level:

$$20 \log_{10} \left( \frac{20}{1} \right) = 26 \text{ dB}$$

The intensity of a sound wave is defined as  $I = \frac{p^2}{\rho c}$ , where  $p$  is sound pressure,  $\rho$  is the medium's density, and  $c$  is the speed of sound in that medium. Intensity is measured in  $\text{W}/\text{m}^2$  and is related to, but not identical to, how humans perceive loudness. Given the vast range of sound pressures in nature, a logarithmic scale called the decibel scale is used to express sound levels.

Another important concept for understanding the transmission and behavior of sound underwater is acoustic impedance.

Sound impedance underwater refers to the opposition a medium (like water) provides to the transmission of sound waves. It is a concept derived from **acoustic impedance**, which is a property of any medium that describes how much resistance it offers to the propagation of sound waves. Sound impedance is crucial in understanding how sound behaves in different environments, especially underwater, as water is denser than air.

$$Z = \rho \cdot c$$

Where: \*  $\rho$  is the density of the medium (in this case, water), typically measured in kilograms per cubic meter ( $\text{kg}/\text{m}^3$ ). \*  $c$  is the speed of sound in the medium, measured in meters per second (m/s).

The acoustic impedances in air and water are vastly different:

$$\text{Air : } Z \approx 340 \text{ kg}/(\text{m}^2 \cdot \text{s})$$

$$\text{Seawater : } Z \approx 1.5 \times 10^6 \text{ kg}/(\text{m}^2 \cdot \text{s})$$

This medium mismatch adds roughly **36 dB** when comparing equal intensities, bringing the total conversion difference to about 62 dB.

So, just remember: - A sound of equal **pressure** is 26 dB higher in water. - A sound of equal **intensity** is 62 dB higher in water.

This is why underwater sound levels appear extremely high compared to airborne values.

Impedance determines how much sound is reflected at boundaries, transmitted, and absorbed. Because water has a vastly higher impedance than air, most sound striking the sea surface from below is reflected, not transmitted. This is why the sea surface acts as a strong acoustic boundary.

## AMBIENT NOISE

Ambient noise in the ocean is a constant background acoustic energy that exists independently of any intentional sound source. It establishes the noise floor against which all sonar systems must operate and governs passive sonar detection limits (the  $N$  in the SNR equation).

Understanding the origin, spectral characteristics, and variability of ambient noise is essential for any realistic prediction of underwater acoustic behavior. Ambient noise comes from three broad categories of sources: environmental processes, biological activity, and anthropogenic (human-made) contributions.

These sources combine to produce the characteristic spectral patterns known as Wenz curves (fig. 41), which are empirical plots that show ambient noise level as a function of frequency. Wenz curves reveal that different physical mechanisms dominate different parts of the acoustic spectrum.

At the lowest frequencies, below roughly 10 Hz, the noise field is controlled by seismic and hydrodynamic processes such as tectonic activity, oceanic microseisms, and large-scale water movement.

Between approximately 10 and 200 Hz, commercial shipping becomes the dominant contributor, with propeller cavitation, engine vibrations, and hull-borne machinery noise raising the noise floor significantly, especially along major shipping routes. At mid-frequencies, from a few hundred hertz to tens of kilohertz, wind, waves, spray, and bubble formation control the spectrum. At very high frequencies, above about 50 kHz, thermal agitation of water molecules sets the ultimate noise floor, producing a uniform and unavoidable background that limits the performance of high-frequency systems.

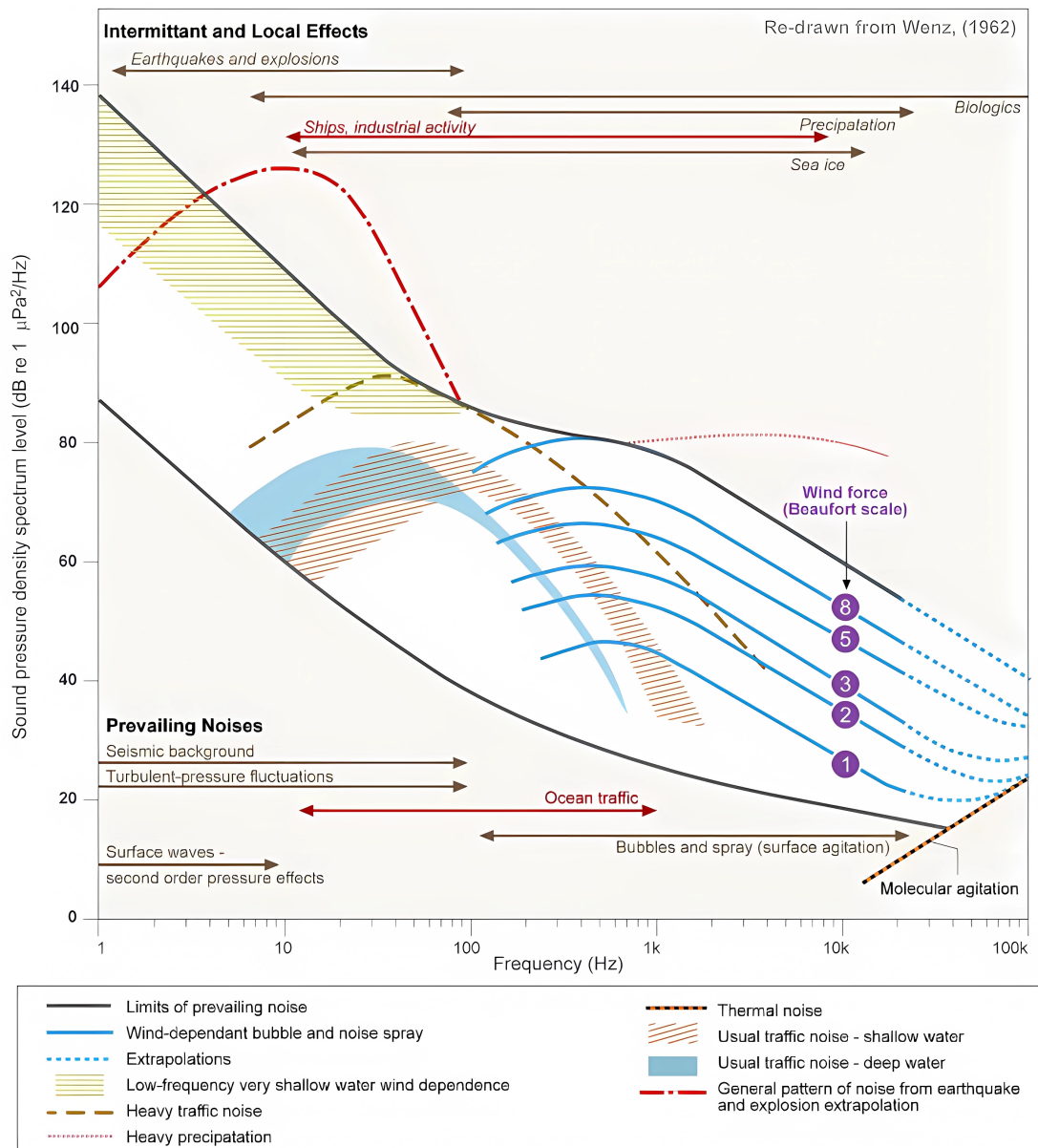


Figure 41: Wenz curves.

**Environmental noise** comprises all naturally occurring physical processes that inject acoustic energy into the water column. Wind and wave noise is the most significant of these, and wind speed is the primary driver of its intensity. As wind increases, wave action strengthens, whitecaps form, and bubbles are entrained and collapse beneath the surface, all of which generate broadband noise. The noise level typically increases by about 5 to 6 dB for each doubling of wind speed, and this contribution dominates the band from roughly 300 Hz to 50 kHz.

Because this noise is strongest near the surface, it can severely degrade passive sonar performance in the surface duct. Rain also contributes broadband noise through droplet impact, bubble entrainment, and surface turbulence, with peak energy between 1 and 20 kHz—an important overlap with many tactical sonar systems. At the opposite end of the spectrum, thermal noise becomes dominant above 50 kHz, arising from the random

molecular motion of water. This noise source is spatially uniform and sets the absolute lower bound on detectable signals at high frequencies. Finally, seismic and geophysical processes contribute low-frequency noise below about 10 Hz, generated by tectonic motion, underwater earthquakes, volcanic activity, and microseisms. Although this noise is not typically relevant to naval sonar, it is important for specialized geophysical and long-range low-frequency systems.

**Biological noise** (or biophony) reflects that the ocean is acoustically active by nature. Marine mammals such as whales, dolphins, and porpoises produce powerful signals across a wide frequency range. Baleen whales generate infrasonic calls between roughly 10 and 200 Hz, while toothed whales produce whistles and clicks extending from 1 kHz to well above 100 kHz. These signals can mask passive sonar, create false detections, or provide environmental cues.

Many fish species also produce sound for mating, territorial defense, and schooling behavior, forming “fish choruses” that often peak between 100 Hz and 2 kHz, particularly in coastal waters at night. In tropical and subtropical regions, snapping shrimp generate intense broadband impulses through cavitation snaps, with energy concentrated between 2 and 20 kHz. Dense shrimp beds can produce some of the loudest biological noise in the ocean and can overwhelm passive sonar in shallow water.

**Anthropogenic noise** has become a major contributor to the modern ocean soundscape, especially at low and mid-frequencies. Commercial shipping is the largest human-made source, dominating the 10–200 Hz band.

Propeller cavitation, engine noise, and hull vibrations combine to raise the ambient noise floor by 20 to 30 dB in heavily trafficked regions, creating persistent noise corridors along major shipping lanes. Industrial and construction activities—such as offshore drilling, seismic airgun surveys, pile driving, dredging, and underwater construction—produce powerful broadband signals that can exceed 200 dB re 1  $\mu$ Pa at the source.

Naval activity also contributes intermittently through active sonar transmissions, torpedo operations, underwater explosions, and machinery noise from submarines and surface ships. Although episodic, these sources can dominate local noise conditions when present.

## PHYSICS OF SOUND PROPAGATION IN THE OCEANS

### SOUND SPEED

The mean sound speed in the oceans is 1500 m/s. For reference, the sound speed in air is 343 m/s (at 20 °C and at sea level) and 6000–7000 m/s in rocks.

The speed of sound in seawater varies as a function of three physical properties of the oceans, which mainly contribute to sound behavior in the water. These are:

- Temperature ( $T$ )
- Pressure or Depth ( $D$ )
- Salinity ( $S$ )

The speed of sound in water can be calculated using empirical equations, such as the Mackenzie equation:

$$c(T, S, D) = A_1 + A_2T + A_3T^2 + A_4T^3 + A_5(S - 35) + A_6D + A_7D^2 + A_8T(S - 35) + A_9TD^3$$

Where: \*  $T$  = temperature in °C \*  $S$  = salinity in parts per thousand (ppt) \*  $D$  = depth in meters

The constants are: \*  $A_1 = 1448.96$ ,  $A_2 = 4.591$ ,  $A_3 = -5.304 \times 10^{-2}$ ,  $A_4 = 2.374 \times 10^{-4}$ ,  $A_5 = 1.340$ ,  $A_6 = 1.630 \times 10^{-2}$ ,  $A_7 = 1.675 \times 10^{-7}$ ,  $A_8 = -1.025 \times 10^{-2}$ ,  $A_9 = -7.139 \times 10^{-13}$

These equations are **empirical**, meaning they are derived from **observations** rather than theoretical principles. Therefore, they are only valid within certain data ranges of depth and geographic areas. For the Mackenzie equation, these ranges are temperatures from 2 °C to 30 °C, salinity from 25 to 40 ppt, and depths up to 8000 meters.

Other empirical equations, such as those from Coppens, Chen and Millero, and Del Grosso, also exist. All provide approximate sound velocities within specific ranges of temperature, salinity, and depth, with an error margin of less than 0.01 m/s.

The average sound speed in seawater is 1500 m/s and varies by only about 10%, or around  $\pm 150$  m/s. That percentage may seem small, but as we will see later, it has an enormous effect on sound propagation behavior.

## SOUND SPEED PROFILE (SSP)

Because the speed of sound in seawater varies primarily with temperature, depth, and salinity, using these 3 variables makes it easy to compute the sound speed and create a graph called the Sound Speed Profile (SSP).

A Sound Speed Profile is a vertical profile of the sound speed on a 2D graph. The X-axis represents sound speed, and the Y-axis represents depth. For example, the figure below shows an SSP near the island of Hawaii in July.

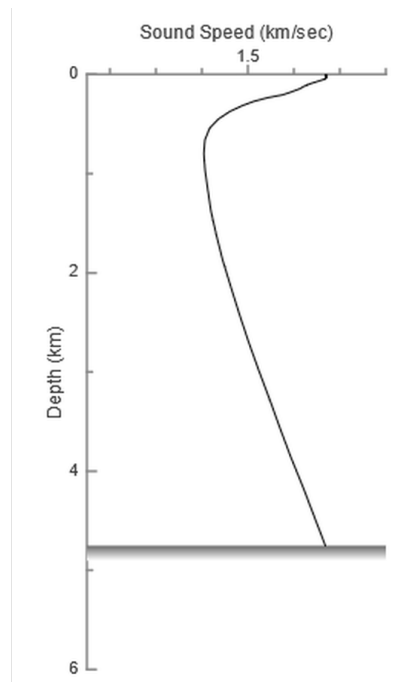


Figure 42: Example of a Sound Speed Profile. Near Hawaii Island in July.

Here are three rules of thumb to estimate the sound speed underwater:

1. **Pressure** (related to depth) consistently increases sound speed. For every 10 meters of depth, sound speed increases by about 0.17 m/s.
2. **Temperature** is the major factor affecting sound speed above 1000 meters; every 1 °C increase in temperature results in a 3 m/s increase in sound speed. Below 1000 meters, the temperature tends to remain relatively constant and doesn't affect the sound speed as dramatically.
3. **Salinity** has the smallest effect on sound speed, increasing sound speed slightly as salinity increases. This is more relevant near river deltas where fresh and saltwater mix. A 1 part per thousand (ppt) increase in salinity results in a 1.3 m/s increase in sound speed.

From the SSP, it's possible to determine the underwater path of sound using a single principle and a single law of physics. This is essential for better use of the detection systems aboard a submarine or a ship. So, entering the chat are Fermat's principle and Snell's law.

### THE SOUND BENDER: FERMAT'S PRINCIPLE AND SNELL'S LAW

Fermat's principle is known as the principle of "least time"; that means a wave will always take the fastest path from point A to point B. A good example you have all experienced is when you throw a rock into a calm pond, the waves propagate outward in a circular pattern.

Sound waves travel spherically in an open ocean until they reach the surface or the seabed. To study the pathway, a simplified method was developed to better understand the propagation. This approach is called ray theory or geometrical acoustics.

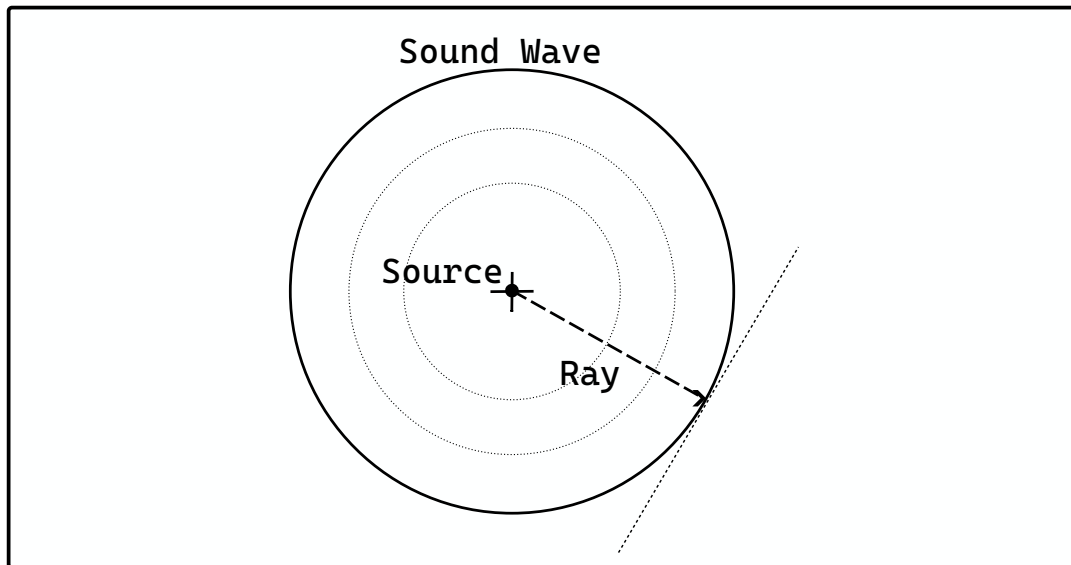


Figure 43: Sound wave and abstract ray.

## SNELL'S LAW

Sound propagation in the water is not as straight as you might imagine. You just learned that it takes the fastest path, which would be a straight line if the medium (the seawater in this case) were uniform with the same density. But the ocean is not a uniform medium (as read earlier in terms of pressure, salinity, and temperature), so the speed of sound varies.

Sound travels faster in warmer water and slower in colder water. This variation causes the refraction of sound waves as they move between these different conditions. A quick rule of thumb is that for each 1 °C increase, the sound speed changes predictably.

Snell's Law describes how light or other waves change direction when they pass from one medium into another with a different refractive index (or when density, temperature, or salinity shifts). The law is named after the Dutch scientist Willebrord Snellius, who first formulated it in 1621.

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{c_2}{c_1}$$

Where  $c_1$  and  $c_2$  are respectively the speed of sound in layers 1 and 2, and  $\alpha_1$  and  $\alpha_2$  are the angles the sound ray travels relative to the normal (vertical or horizontal axis).

This equation means: \* If sound speed decreases,  $\sin \alpha$  must decrease → the ray bends toward the slower medium. \* If sound speed increases,  $\sin \alpha$  must increase → the ray curves outward.

This is the mathematical expression of the “sound is lazy” principle: **sound always bends toward the region of slower sound speed.**

When the sound velocity gradient is positive (i.e., the speed of sound in water increases with depth), the ray bends upward; conversely, when the gradient is negative (i.e., the

sound speed decreases with depth), the ray bends downward, as shown in the next figure.

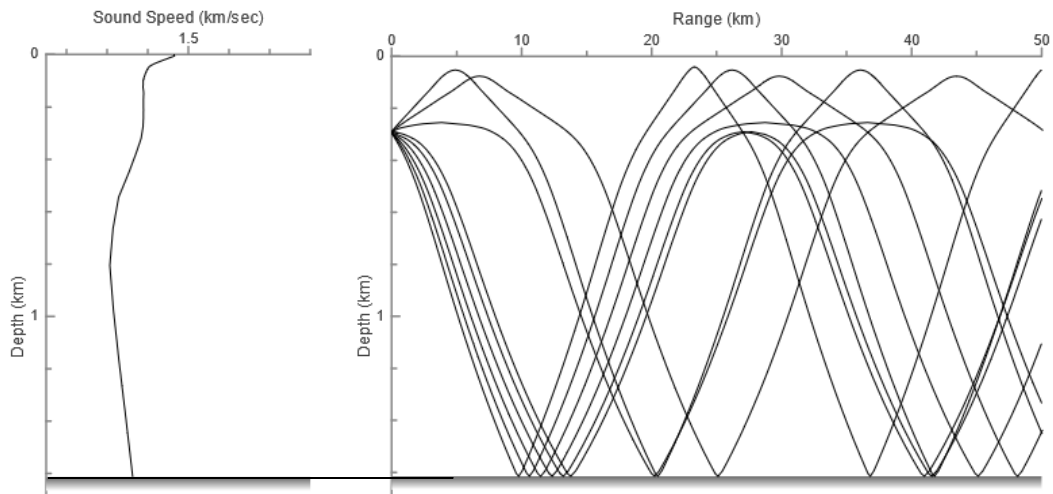


Figure 44: Example of sound propagation and associated SSP. The “sound” source is located at -250m.

A quick tip to remember this reaction is to think of a smiley:

Gradient	Ray Direction	Reaction
Negative	Downward	Bad
Positive	Upward	Good

### RAY (TRACING) THEORY

Ray tracing in the context of underwater sound propagation has nothing to do with ray tracing in a modern GPU!

A ray is an abstract line that represents the path along which sound energy travels. It is perpendicular to wavefronts (surfaces of constant phase) and helps visualize how sound moves through a medium—in this case, seawater.

Ray theory treats sound as a collection of infinitesimally thin rays that follow the paths predicted by Snell’s Law. It is valid when the medium varies smoothly with depth and frequencies are above a few hundred hertz. (This limitation comes from the fact that ray tracing theory assumes the acoustic wavelength ( $\lambda$ ) is significantly smaller than the dominant structural scales, here the depth  $H$ ). Another issue is that ray models largely fail to capture diffraction when encountering a seamount (sound bends around it instead of cleanly diffracting), but that’s well beyond the scope of this introduction to sound propagation.

The curvature of a ray is determined by the **vertical gradient** of sound speed:

$$\frac{d\theta}{dz} \propto -\frac{dc}{dz}$$

So if you have a: \* **Negative Gradient** ( $\frac{dc}{dz} < 0$ ): Sound speed decreases with depth → rays bend **downward**. This typically occurs in thermoclines. \* **Positive Gradient** ( $\frac{dc}{dz} > 0$ ): Sound speed increases with depth → rays bend **upward**. This occurs in deep water where pressure dominates. \* **Rays refract toward the minimum**: This forms the **Deep Sound Channel**.

This is the physical mechanism behind the long-range propagation that this text will present later on.

## THE CRITICAL ANGLE

The critical angle is the maximum incidence angle at which a sound ray can still pass from a slower layer into a faster layer without experiencing total internal reflection.

$$\theta_c = \sin^{-1} \left( \frac{c_1}{c_2} \right)$$

Where: \*  $\theta_c$  = critical angle \*  $c_1$  = sound speed in the upper medium \*  $c_2$  = sound speed in the lower medium

If  $c_2 > c_1$ , refraction occurs up to this limit. Beyond  $\theta_c$ , total reflection occurs.

What does this mean specifically? It's simple: when a ray reaches the surface, over 99% of the sound is reflected downward (depending slightly on the sea state, the presence of bubbles, etc., though their immediate effect is usually negligible). When a ray reaches the seabed, it is reflected upward, but depending on the composition of the sediment, it can result in a weak (mud), moderate (sand), or strong (rock) reflection.

## ATTENUATION AND SPREADING LOSS

Like in air, sound loses energy as it travels. Two mechanisms play primary roles: spherical spreading and cylindrical spreading. Imagine sound propagating like a bubble expanding in the water. The surface area  $S$  of the sphere is given by the equation below. If the radius  $r$  doubles, the surface area quadruples.

$$S = 4\pi r^2$$

Where: \*  $S$  = Surface area \*  $r$  = Radius of the sphere

Because the sound wave propagates outward, the same amount of initial energy is spread across an increasingly larger surface, meaning the sound intensity diminishes at any single point on that expanding sphere.

Spherical spreading loss happens in deep water with no limiting boundaries (like the surface or seabed). The loss in decibels is calculated using the formula below:

$$\text{Loss} = 20 \log_{10}(r)$$

This means that each time the distance doubles, there is a **6 dB** loss.

When sound becomes trapped between boundaries like the surface and the sea floor, cylindrical spreading is used to determine the loss instead. Cylindrical spreading losses

are less severe than spherical losses because the area does not quadruple when  $r$  doubles; only the curved profile area expands linearly.

$$V = \pi r^2 h$$

Where: \*  $V$  = Volume \*  $r$  = Radius of the cylinder \*  $h$  = Height of the cylinder

The transmission losses are given by the equation below:

$$\text{Loss} = 10 \log_{10}(r)$$

In this environment, doubling the distance results in only a **3 dB** loss.

## ABSORPTION AND SCATTERING: OTHER FACTORS AFFECTING SOUND PROPAGATION

### ■ Absorption

Absorption refers to the process by which sound energy is converted into heat as it propagates through water, resulting in a gradual reduction in sound intensity over distance.

The absorption of sound in water is strongly frequency-dependent. At low frequencies (below ~1 kHz), absorption is minimal, allowing sound to travel thousands of kilometers (as seen in the SOFAR channel). At higher frequencies, absorption increases rapidly, severely limiting the range of high-frequency sonar and communication systems. Absorption is expressed in **dB/km**.

The primary mechanisms of absorption in water are chemical relaxation, viscous losses, and thermal conduction.

- **Chemical relaxation:** In seawater, certain dissolved ions (notably magnesium sulfate and boric acid) undergo molecular relaxation processes that absorb sound energy, especially at specific frequency ranges. Boric acid absorption peaks at frequencies around 1 kHz, while magnesium sulfate ( $\text{MgSO}_4$ ) peaks between 1–100 kHz.

As shown by Table 4, absorption is minimal at lower frequencies, which is why low-frequency signals travel so far underwater.

Table 4: Absorption for  $\text{MgSO}_4$  (magnesium sulfate), boric acid, and pure water at different frequencies.

Frequency	Boric Acid	Magnesium Sulfate	Water	Total
100 Hz	0.07 dB/km	0.0004 dB/km	0.00001 dB/km	0.07 dB/km
1 kHz	0.9 dB/km	0.04 dB/km	0.0001 dB/km	0.94 dB/km
10 kHz	0.1 dB/km	1.5 dB/km	0.01 dB/km	1.6 dB/km
100 kHz	0.001 dB/km	0.4 dB/km	20 dB/km	20.4 dB/km

- **Viscous losses:** This refers to the friction between oscillating water molecules that dissipates wave energy as heat. This primarily impacts frequencies  $> 100$  kHz.
- **Thermal conduction:** This involves heat transfer due to tiny temperature gradients created by the compression cycles of the sound waves themselves.

The second phenomenon that impacts sound propagation is scattering.

## ■ Scattering

Surface waves and other irregularities can scatter sound waves in different directions. But what is the difference between scattering and bouncing? Well, it's simple! Bouncing is a specular reflection (like a mirror), while scattering is a diffuse reflection (spreading out in many directions)!

In plain terms, the difference depends on the medium's roughness relative to the acoustic wavelength.

The Surface Roughness Amplitude (SRA) is a measure of the medium's profile roughness (Table 5), which is the average height of the irregularities on a surface boundary (be it a sandy or rocky seabed, or a calm vs. rough sea surface state). It is usually calculated by the root-mean-square (RMS) height or peak-to-trough height of the surface irregularities over a specified spatial scale.

The acoustic wavelength is the speed of underwater sound divided by the frequency.

$$R = \frac{\text{SRA}}{\lambda}$$

Where: \*  $\lambda$  is the acoustic wavelength. \* SRA is the Surface Roughness Amplitude.

- If  $R < 1$ , specular bouncing occurs.
- If  $R > 1$ , diffuse scattering occurs.

Table 5: Mean Surface Roughness Amplitude of different substrates.

Seabed Type	Typical SRA
Soft mud	1–10 mm
Fine sand (flat)	5–20 mm
Rippled sand	2–10 cm
Pebble/gravel	5–20 cm
Rocky seabed (blocky)	0.1–1 m

The acoustic wavelength depends directly on the frequency and speed of sound underwater:

$$\lambda = \frac{c}{f}$$

Where: \*  $\lambda$  is the acoustic wavelength. \*  $c$  is the sound speed in the medium (m/s). \*  $f$  is the frequency (Hz).

Sound propagation is complex; there are losses, reflections, refractions, absorption, scattering, and bouncing. Some of you may already know tactical maneuvers that exploit these properties, like bottom bouncing.

Underwater sound does not propagate randomly. Instead, depending on the sound speed profile, boundary conditions, and source depth, sound energy organizes itself into a limited number of canonical propagation paths. These six paths form the foundation of all sonar performance predictions.

## THE SIX BASIC PATHS OF SOUND UNDERWATER

Sound can travel along an infinite number of paths, but it generally categorizes into six basic paths depending on distance, the geometry between the emitter and the receiver, and the sound propagation characteristics of the ocean:

- Direct Path (DP)
- Bottom Bounce and Surface Bounce (BB / SB)
- Surface Duct (SD)
- Deep Sound Channel (DSC)
- Reliable Acoustic Path (RAP)
- Convergence Zone (CZ)

### DIRECT PATH

This occurs when the sound follows a direct line between the receiver and the emitter. This usually happens when the two are at a short distance from each other ( $< 10$  km). It's the simplest case of sound propagation. When the sound speed profile is uniform, the rays do not bend up or down and travel straight, as shown in the figure below. Where the SSP graph is almost vertical at around -400 m, meaning there is no change in sound speed, the rays follow a direct path.

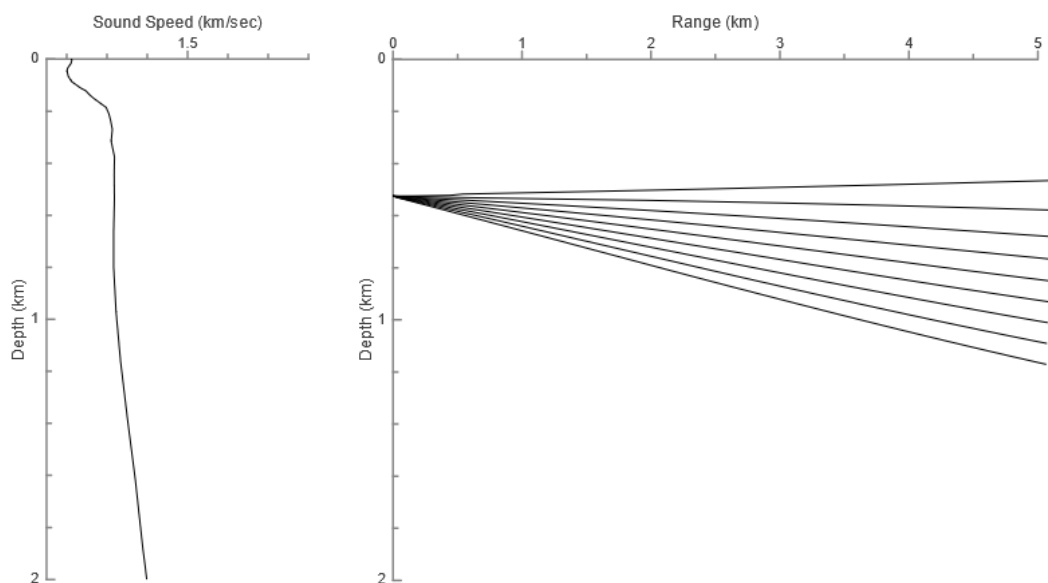


Figure 45: Direct path.

Sound traveling through the water is constrained by two boundaries: the bottom and the surface, each acting as an acoustic mirror reflecting the sound energy.

### BOTTOM BOUNCE AND SURFACE BOUNCE PATH

When sound reaches the seabed, it encounters a new medium—be it rock, mud, or sand—with a completely different density. The sound speed changes rapidly, so Snell's law applies, and the sound is mostly reflected upward at an angle.

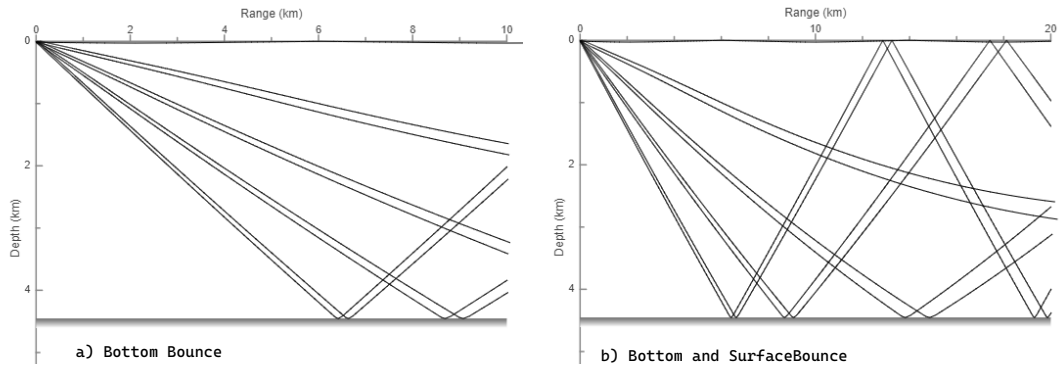


Figure 46: Bottom bounce.

The next three paths (SD, DSC, and RAP) belong to the duct pathing category. One happens at the surface, the DSC sits around 1000 m, and the RAP operates even deeper.

In the world of underwater acoustics, a “duct” is a distinct scenario where sound is guided along a constrained path, behaving much like water moving through a pipe.

### SURFACE DUCT PATH (SDP)

Before looking at the SDP, another structural depth must be introduced: the **Sonic Layer Depth (SLD)**. The SLD is defined as the **depth of maximum sound speed above the deep sound channel axis** and is obtained directly from the Sound Velocity Profile (SVP), as shown in this figure.

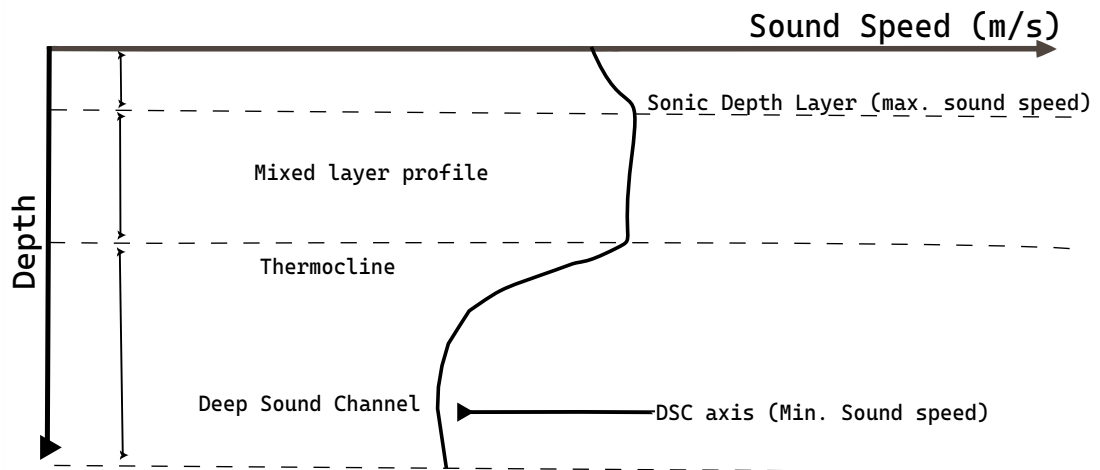


Figure 47: Sonic Layer Depth (SLD).

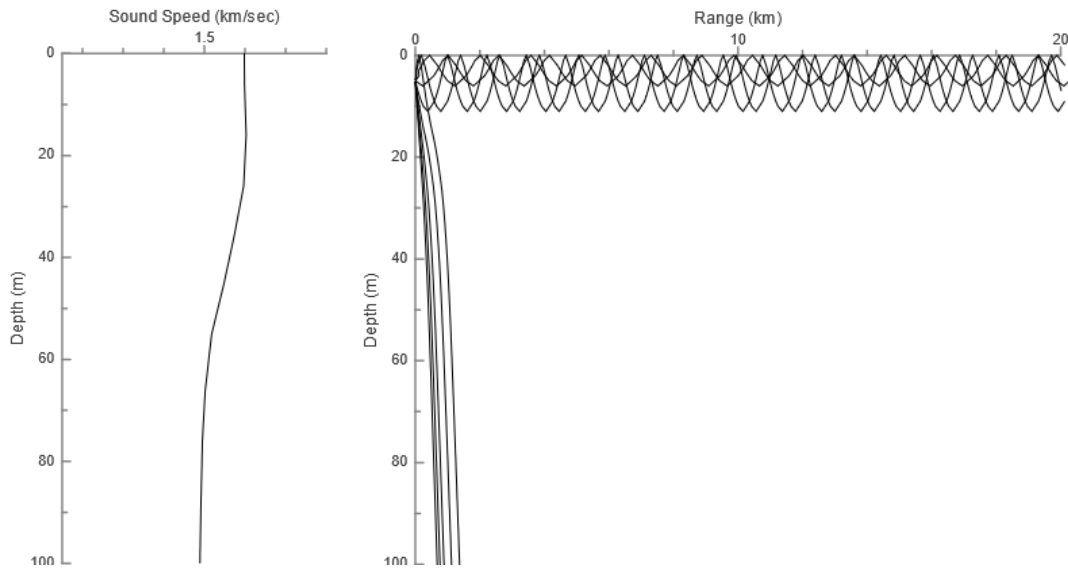


Figure 48: Surface duct.

The surface duct occurs between the surface and the Sonic Layer Depth (SLD), as shown in the figure above; the SLD occurs at around 15 m below the surface in this example. Note that when this layer forms, surface ships' sonar detection ranges can be severely limited. To counter this blind spot, most navies use Variable Depth Sonar (VDS).

### DEEP SOUND CHANNEL (DSC) PATH

This path was discovered during WWII and called the SOFAR (SOund Fixing And Ranging) channel. It was originally used to locate downed airplane crews. Aircrews would drop a small explosive charge designed to detonate at a specific depth; listening stations receiving the sound of the blast could triangulate the exact position so search and rescue planes could be dispatched. Later, during the Cold War, this method evolved to locate missile splashdowns in the ocean via the Missile Impact Location System (MILS).

When a sound source is located in or near the sound speed minimum, the sound rays are trapped in a channel bounded above and below (see the next figure). The sound waves are continuously focused back toward the channel axis by refraction. A positive gradient bends rays upward, while a negative gradient bends rays downward, trapping the energy over vast distances.

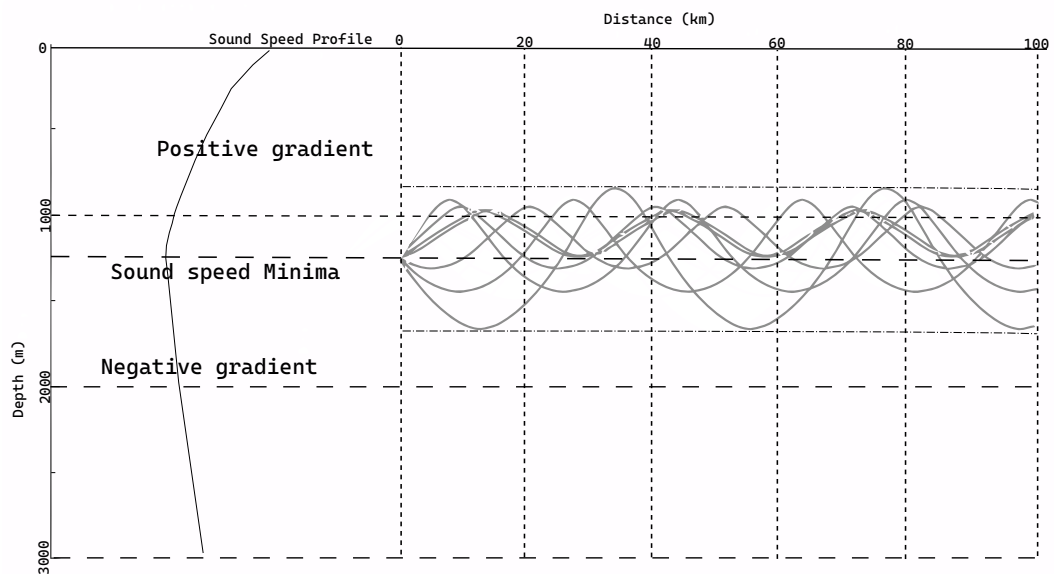


Figure 49: Deep sound channel (DSC).

### RELIABLE ACOUSTIC PATH (RAP)

The RAP is an important acoustic duct in the deep ocean that occurs when the receiver is placed near the bottom, at or below the critical depth—where the deep sound velocity matches or exceeds the maximum sound velocity found near the surface. In a RAP environment, transmission loss is relatively low because the sound paths do not continuously strike the scattering surface or absorbing bottom. Energy is preserved, and there is no mid-range blind zone.

The RAP is highly utilized in deep-sea surveillance architectures, such as the Integrated Undersea Surveillance System (IUSS).

The final path is one of the most famous, but easily the most complex of the six.

### CONVERGENCE ZONE PATH (AND SHADOW ZONE)

A Convergence Zone (CZ) is a deep-ocean phenomenon where sound rays from a near-surface source bend downward due to high pressure, then refract back toward the surface in a massive focusing arc. These zones create high-intensity rings of sound at the surface about 30–60 km (20–35 miles) apart, drastically boosting the detection of distant targets by up to 10–20 dB.

CZ propagation requires deep water, usually more than 2000 meters (6000 feet).

When the refracted rays converge near the surface, they create a caustic zone—a high-intensity focal region where multiple sound rays intersect due to the continuous bending across different water layers. When these rays meet at the same location, they concentrate acoustic energy (Fig. 22).

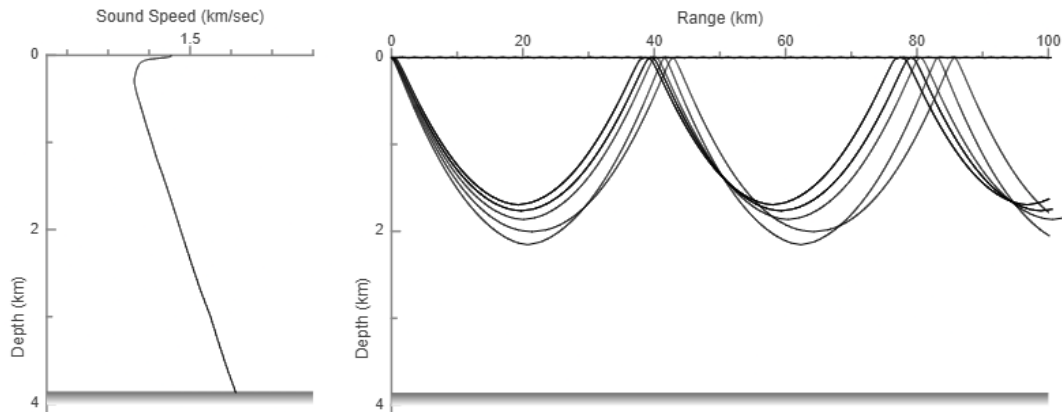


Figure 50: Example of a Convergence Zone. A caustic zone is visible at 40km.

Note that caustic zones can also form within the Deep Sound Channel.

Most of the time, where you find a caustic zone, you will also encounter a shadow zone.

### ■ Shadow Zone

Alongside the Convergence Zone, the shadow zone is an acoustic phenomenon your readers are bound to recognize. A shadow zone is a region in the ocean where sound energy is severely reduced because refraction bends acoustic rays completely away from that area, preventing them from reaching it.

A shadow zone forms when the sound speed profile causes rays to curve sharply upward or downward, leaving a particular depth–range region devoid of direct acoustic paths. In a negative sound-speed gradient, for example, sound bends downward, leaving a low-intensity region above the profile; in other profiles, the opposite can occur (Fig. 51). The result is a distinct acoustic void where signal intensity drops sharply because rays are refracted away rather than transmitted through.

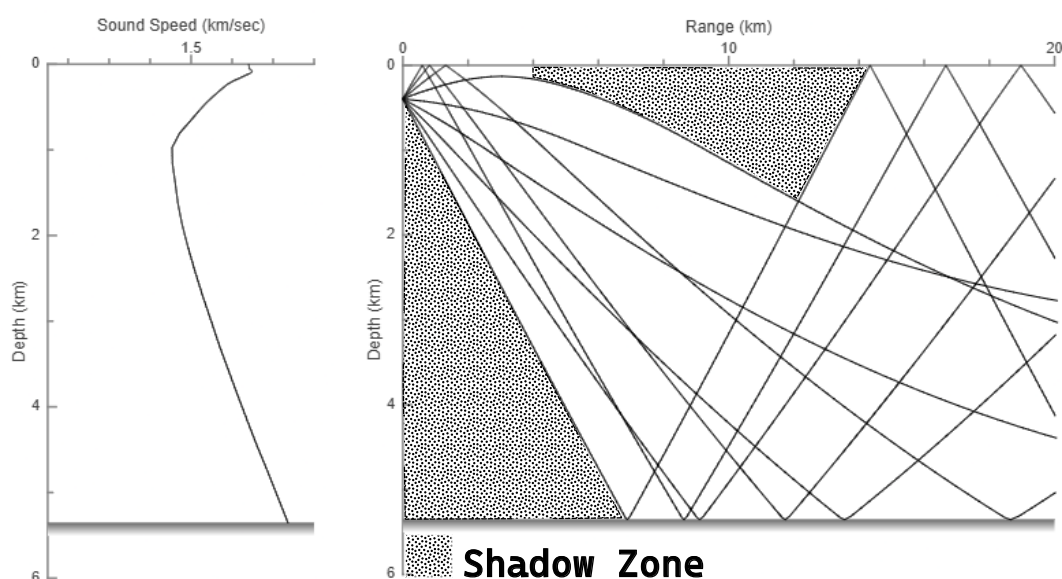


Figure 51: Example of shadow zones. Receiver at -400m.

These basic sound paths can mix, creating a wide variety of dynamic underwater sound environments (Table 6). It is very rare to experience only one of these basic paths in isolation. On the TDA (Tactical Display Area) screen of the sonar station in Modern Naval Warfare (MNW), always look out for these configurations and track the areas where caustics will form. Those are the absolute best places to detect targets—or to accidentally be detected yourself!

Propagation Path	Key Feature	Typical Range	Best Conditions
Direct Path	Straight or gently curved lines	Short (<10 km)	Weak SSP gradients
Bottom Bounce	Reflection off the seabed floor	Medium–Long	Hard, rocky, or sandy reflective bottom
Surface Duct	Trapped near the surface boundary	Long	Warm mixed surface layer with defined SLD
Deep Sound Channel	Trapped at mid-depth speed minimum	Very Long	Strong, deep SOFAR velocity minimum
Reliable Acoustic Path	Deep source to surface refraction	Long	Deep ocean water with a positive deep gradient
Convergence Zone	Focused surface refraction rings	Very Long	Deep water (>2000 m) + strong thermocline

Table 6: Summary of underwater sound propagation paths.



# SONAR

SONAR means **Sound Navigation And Ranging**. The first SONAR was researched and developed after the Titanic disaster in 1912; it was the Fessenden Oscillator, a very crude active SONAR. The two world wars and the Cold War have contributed significantly to the research and development of new technologies.

Movies often represent modern SONAR as constantly “pinging” to detect a target. In reality, there are two main types of SONAR: Passive and Active.

## THE ACTIVE SONAR

Active sonar uses an array of transducers to generate a sound wave at specific frequencies. That wave reflects off objects and allows the submarine to determine their range and bearing. However, it has a major drawback: the emission of the active sonar can be detected far beyond the maximum distance at which it can successfully receive an echo. It’s like using a flashlight at night to find someone; they will see the light beam well before you can spot them.

Modern submarines tend to rely solely on passive systems to remain invisible to the enemy, allowing them to detect and track a target from distances exceeding 100 km.

## PASSIVE SONAR

There are a few forms of passive sonar. Currently, submarines are equipped with:

1. **Bow sonar:** Cylindrical, spherical, or, like on the *Virginia*-class, a horseshoe-shaped Large Aperture Bow (LAB) array.
2. **Flank Array:** These SONAR arrays are mounted on the hull flanks of the submarine. They are capable of determining the bearing and range of a target very easily since the transducers are aligned on a large, stable plane.
3. **Towed Array:** These are long lines of transducers towed far behind the submarine so they are not disturbed by the self-generated noise of the vessel’s own machinery.

To estimate the performance of a SONAR system, a set of equations was developed during WW2 to evaluate equipment performance. This value is known as the **Figure of Merit (FOM)**.

## THE SONAR EQUATIONS

The equations presented here are simplified to showcase basic underlying concepts. Real operational equations are strictly classified and require both an advanced knowledge of sound propagation and a Top Secret clearance to access the Special Access Programs (SAP) regarding active naval intelligence data.

To simplify to a maximum, a SONAR equation takes into consideration three types of variables: \* The environment \* The target \* The detecting equipment and the hosting submarine

**Environment related:** Refers to all the negative impacts of the medium, like the sea state, the type of sound propagation paths, the frequency windows, and other factors. The two main parameters are: \* **Transmission Loss (TL):** The drop in acoustic intensity due to spreading, absorption, and scattering over distance. \* **Ambient Noise Level (NL):** Background noise generated by meteorology, civilian traffic, the type of seabed, and regional bathymetry.

**Equipment related:** Takes into account the stealthiness of the submarine and the technology of the SONAR suite. \* **Self-Generated Noise (SGN):** Own-ship radiated noise, which includes machinery noise, propeller cavitation, flow noise, and platform speed (often the dominant factor limiting detection). \* **Detection Threshold (DT):** The signal-to-noise ratio required at the processor output for a human operator or automated system to confidently declare a detection. \* **Directivity Index (DI):** The detecting equipment's array gain, describing its ability to filter out background noise from other directions.

**Target Related:** Similar to own-ship equipment parameters, but evaluated for the contact of interest (whether it is an enemy submarine or a surface ship). \* **Target Source Level (TSL):** The acoustic energy radiated by the target (machinery, flow noise, etc.). \* **Target Strength (TS):** The target's echo reflectivity, used specifically in active sonar operations.

In summary, the different variables used to compute the **Signal Excess (SE)** are: \* **TSL:** Target Source Level (target radiated noise) \* **TL:** Transmission Loss (environment) \* **NL:** Ambient Noise Level (environment) \* **SGN:** Self-Generated Noise (own-ship noise) \* **DI:** Directivity Index (detecting equipment's array gain) \* **DT:** Detection Threshold (detecting equipment)

## THE EQUATION FOR THE PASSIVE SONAR

$$SE = TSL - TL - (NL + SGN - DI) - DT$$

If the **Signal Excess (SE)** is  $> 0$ , the target is detected.

## THE EQUATION FOR THE ACTIVE SONAR

- **SL:** Active transmitted signal level (the SONAR "ping").
- **TS:** Target Strength (the target's echo reflectivity).
- **2TL:** Double transmission loss, because the signal must travel back and forth between the transmitter, target, and receiver.

$$SE = SL - 2TL + TS - (NL + SGN - DI) - DT$$

If the **Signal Excess (SE)** is  $> 0$ , the target is detected.

Even though these equations look simple, each variable is actually the product of multiple engineering sub-systems and proprietary processing parameters. These details are kept strictly confidential so that an adversary cannot deduce your submarine's exact acoustic signature, the sensitivity of your SONAR suite, or the extent of your intelligence data regarding their platforms.

Over the years, the Detection Threshold (DT) has improved greatly due to larger bow SONAR arrays, long Towed Arrays, and modern structural flank arrays. However, the physical dimensions of these systems remain constrained by the internal volume of the hull. The introduction of computers during the Cold War and digital processing algorithms transformed filtering capabilities, allowing navies to track increasingly stealthy submarines. One of the most critical advancements in improving the DT is beamforming.

## BEAMFORMING

Beamforming is a digital processing technology you likely use every day without knowing it; for instance, modern 5G cellular networks rely on it to focus signals between towers and your smartphone.

Underwater, beamforming takes advantage of the numerous individual transducers installed across a sonar network (whether in a bow, flank, or towed array). While the underlying mathematics can be dry, the practical purpose of this technique is straightforward: to mathematically focus the array in a specific direction, enhancing the received signal power while keeping directional background noise as low as possible.

There are multiple algorithms available to achieve this goal, but for simplicity, we will examine the classic “**delay-and-sum beamformer**”.

## THE DELAY-AND-SUM BEAMFORMER

Imagine a basic SONAR array composed of only three hydrophone elements ( $T_1$ ,  $T_2$ , and  $T_3$ ). If an incoming acoustic wave arrives from an angle, the sensors will receive the same wave crest at three slightly different times because they do not lie on the same spatial plane relative to the advancing wavefront. This small difference in arrival time is typically measured at microsecond or nanosecond scales.

The time delay between the incoming wavefront hitting adjacent transducers can be calculated using the following geometric equation:

$$\Delta t = \frac{d \sin \theta}{c}$$

$\Delta t$  is the time delay between adjacent hydrophones.

$d$  is the element spacing.

$c$  is the sound speed in water.

$\theta$  is the steering angle.

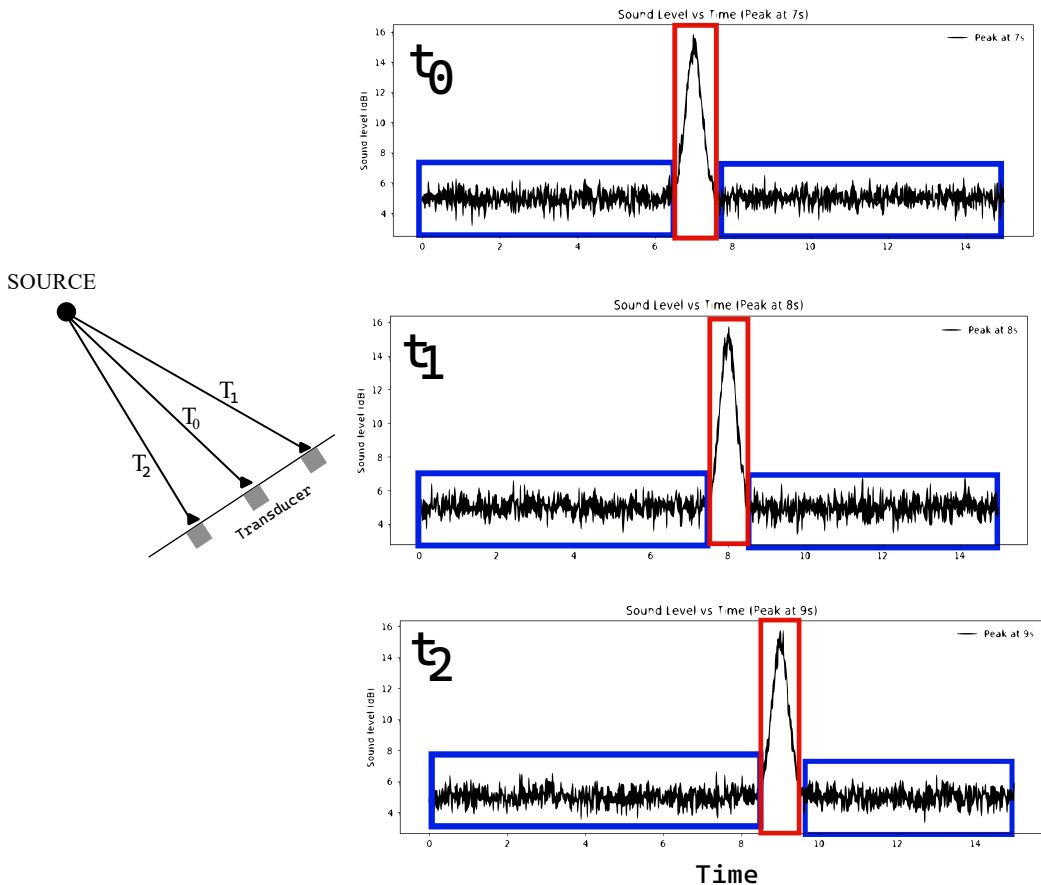


Figure 52: Signal received by 3 transducers ( $T_1$ ,  $T_2$  and  $T_3$ ) at 3 different times ( $t_1$ ,  $t_2$  and  $t_3$ ).

The total raw signal entering the array is composed of a coherent part and an incoherent part. A coherent signal is defined by: \* It originates from **one specific direction**. \* The **phase relationship** of the wave between hydrophones remains stable. \* After applying artificial steering delays to account for geometry, the signals **align perfectly**.

On the other hand, the incoherent background noise is characterized by: \* The phase is **random** from sensor to sensor. \* It exhibits no stable direction of arrival. \* It cannot be neatly aligned by steering delays.

The diagram above shows a signal captured by three transducers ( $T_1$  to  $T_3$ ), each receiving the incoming wave at different times ( $t_1$  to  $t_3$ ). The coherent part of the signal (indicated in red) is identical across all three channels and can be superposed exactly when the correct time delays are applied. In contrast, when the random, incoherent noise (indicated in blue) is added together, the peaks and troughs cancel out or average out into a non-distinctive, low-energy signal.

Let's look at the mathematical impact of this alignment. Suppose a signal is arriving at a baseline level of 16 dB. First, we convert this value from decibels to its equivalent linear power:

$$P = 10^{\frac{L}{10}}$$

$P$  is the Linear Power.

$L$  is the level in dB.

For a 16 dB input signal, the linear power value is approximately 39.81.

Since our delay-and-sum beamformer artificially shifts the channels to align the wave crests, we add the linear power of the three synchronized channels together:

$$39.81 \times 3 = 119.43$$

Converting this summed power back to the decibel scale yields:

$$10 \log_{10}(119.43) \approx 20.77 \text{ dB}$$

The net gain achieved by processing the signal across the array is:

$$20.77 \text{ dB} - 16 \text{ dB} = 4.77 \text{ dB}$$

The beamforming process has added 4.77 dB to our signal. While that might sound like a small number, remember that on a logarithmic scale, an increase of 4.77 dB effectively multiplies the original signal power by three times relative to the background noise.

To summarize this relationship for any array where  $N$  equals the total number of aligned transducer elements: \* Coherent signals **add in amplitude**, yielding an  $N^2$  **power gain**.  
\* Incoherent noise **adds only in power**, yielding a modest  $N$  **power gain**.

The resulting Array Gain (AG) or SNR improvement is equal to:  $G_{\text{power}} = 10 \log_{10}(N)$  expressed in dB, obtained through the coherent summation of signals in a sonar array.

Array Size (N)	Power Gain (dB)	SNR Improvement Factor
1	0 dB	No change in SNR
3	4.77 dB	3x SNR improvement
10	10 dB	10x SNR improvement
30	14.77 dB	30x SNR improvement
100	20 dB	100x SNR improvement

Table 7: Relation between the number of transducers used, array gain, and output level.

As demonstrated in Table 7, increasing the number of active transducers yields a major boost in processing gain. However, there is a physical and computational limit to how much raw data can be ingested and processed simultaneously, even when relying on modern fiber-optic arrays and high-performance computing hardware.

When you consider that this intensive digital processing is occurring simultaneously across the bow array, flank arrays, and towed arrays, it becomes clear why modern submarine combat systems require robust liquid cooling architectures.

Beyond simple delay-and-sum processing, engineers utilize advanced high-resolution spatial processing algorithms such as Bartlett, Capon, MUSIC (Multiple Signal Classification), or ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques). Researchers often design memorable acronyms to avoid repeating dense technical titles in daily operations.

The field of naval sonar acoustics sits at the absolute cutting edge of signal processing and structural engineering. These advancements—extending from physical hydrophone design to complex data filtering algorithms—allow modern sonar technicians to detect, classify, and track contacts faster and at longer ranges.

A significant portion of modern acoustic research focuses directly on the unique challenges of shallow-water environments.

### **ACOUSTICS IN SHALLOW WATERS**

For an oceanographer, shallow waters are defined as the coastal marine zones stretching between the shoreline and the edge of the continental shelf. For a submariner, this environment extends from the coast down to a depth of approximately 500 meters, encompassing roughly 10% of the world's total oceanic surface area.

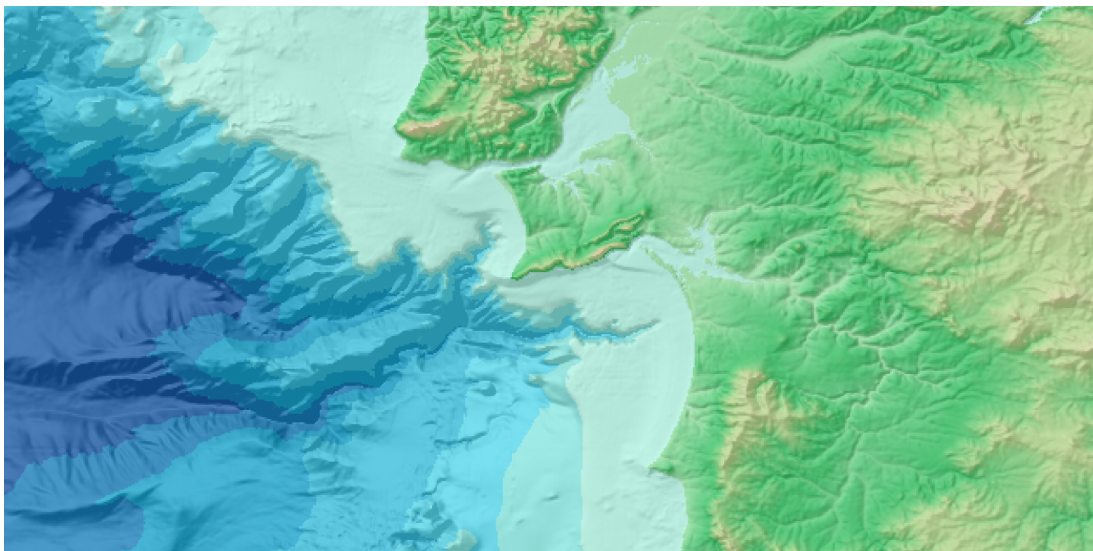


Figure 53: Example of shallow water bathymetry.

Shallow-water acoustics differ drastically from deep-ocean propagation because the seafloor near continental shelves is highly irregular, characterized by sudden slopes, shallow trenches, and underwater canyons (Fig. 53). These complex geological features trigger massive acoustic backscattering, constant reverberation, and severe bottom attenuation. Furthermore, because the surface and the seafloor are physically close together, propagating sound waves interact rapidly with both boundaries, resulting in relentless wave bouncing and complex multi-path interference.

These waters present an extreme operational challenge. Coastal zones are frequently crowded with intense commercial maritime traffic, industrial shipping, and local fishing fleets, generating a dense, noisy background environment. However, this high ambient noise level also offers excellent opportunities for a stealthy submarine to hide from

active search teams. Intelligence-gathering missions, littoral surveillance, and special operations deployment occur almost exclusively within these complex shallow zones.

To defend these highly contested spaces, navies typically deploy ultra-quiet diesel-electric submarines (SSKs) equipped with Air-Independent Propulsion (AIP) systems. These platforms can remain submerged and nearly silent for weeks at a time, making them exceptionally dangerous adversaries in shallow water. Consequently, these littoral zones are heavily patrolled by land-based Maritime Patrol Aircraft (MPA) and specialized anti-submarine warfare (ASW) helicopters utilizing dipped sonars and dense sonobuoys.

## WHY NOT USE RADAR OR LASER?

Given that modern electronic sensors like RADAR and LASER work with incredible precision across the atmosphere and space, it is natural to ask why they cannot be deployed to detect, classify, and track submerged contacts. While researchers have attempted to adapt optical and radio sensors to the marine environment for decades, these systems fail due to the fundamental physical and chemical properties of seawater.

## LASER UNDERWATER

Laser architectures have been thoroughly evaluated as potential tools for airborne maritime surveillance and submarine detection. Among all visible wavelengths of electromagnetic radiation, blue-green lasers—operating within the narrow 450–550 nm spectral band—exhibit the highest penetration capability through water. This phenomenon occurs because the molecular absorption spectrum of seawater drops to a relative minimum within this specific optical window.

Nevertheless, even these optimized wavelengths encounter massive attenuation when passing through a marine environment. In exceptionally clear, open-ocean conditions, a blue-green laser beam can penetrate to a maximum depth approaching 100 meters under ideal circumstances. In standard operational settings, however, the effective range is vastly shorter. In coastal waters containing suspended sediment, organic particulates, or microscopic biological life, useful light penetration is frequently restricted to 10–20 meters, and it can drop to a few meters in highly turbid or muddy environments. This rapid degradation is caused by a combination of absorption and diffuse scattering, both of which scale up dramatically with water turbidity.

The attenuation coefficient for blue-green laser light typically ranges from 0.1 to 1 dB per meter in clean water. While a loss of 1 dB/m sounds modest, these values compound exponentially over distance. At an attenuation rate of 1 dB/m, approximately 20% of the laser's optical power is lost with every single meter of travel; by the time the beam propagates just 5 meters, only about one-third of its initial energy remains. In clear water, cumulative dissipation leaves only ~10% of the original signal at 10 meters, and less than 1% survives at 20 meters. In turbid coastal waters, attenuation coefficients soar to 3–10 dB/m, causing a catastrophic 90–99% loss of beam power within the first meter of penetration.

Several distinct physical phenomena restrict the utility of underwater optical systems:

- \* **Water Clarity:** Suspended sediment and organic materials absorb photons and scatter light particles out of the beam's path.
- \* **Backscatter:** Scattered photons reflect directly back into the laser receiver, generating blinding background noise and crippling the sys-

tem's signal-to-noise ratio. \* **Beam Diffusion:** The continuous collision of photons with water molecules causes the laser beam to widen and diffuse over distance, destroying its spatial coherence and preventing it from resolving clear structural shapes.

These rigid physical constraints restrict modern laser systems to highly specialized, shallow-water profiles. Airborne platforms, such as the Airborne Laser Mine Detection System (ALMDS) or helicopter-borne LiDAR sensors, leverage the blue-green window effectively to survey shallow shipping lanes and map near-shore naval mines where the beam can reach the seafloor and bounce back. However, their utility disappears entirely against deep targets. Submarines operating below 100 meters remain completely immune to laser-based detection arrays due to the rapid, unavoidable dissipation of light energy in seawater.

While lasers struggle in the upper layers of the ocean, standard RADAR systems fare even worse. Let's examine why radio frequency detection is entirely useless beneath the surface.

## RADAR UNDERWATER

Despite extensive military experimentation to adapt high-power RADAR arrays for underwater tracking, radio wave detection in the ocean is physically impossible.

RADAR systems rely on high-frequency electromagnetic radio waves, which are instantly absorbed, scattered, and grounded upon contacting seawater. The primary driver of this failure is the high electrical conductivity of ocean water, which stems directly from its dissolved salt content.

Saltwater acts as an incredibly efficient electrical conductor, which serves to instantly attenuate and dissipate radio frequency energy. For example, consider a relatively low radio frequency of 10 MHz. In the open atmosphere, a 10 MHz signal can propagate over thousands of kilometers by refracting off the Earth's ionosphere. However, upon hitting seawater, its maximum penetration depth is instantly choked down to a few centimeters.

The attenuation rate at this frequency typically sits between 100 and 200 dB per meter, meaning that virtually all transmitted power is converted into heat within the first meter of water. As you move to higher frequencies, these transmission losses escalate exponentially.

In the gigahertz (GHz) microwave bands common to standard military radar systems (such as the L, S, or X bands), the attenuation rate regularly reaches a staggering 1,000 dB per meter. This represents a mathematical power reduction factor of  $10^{100}$ . Under these real-world conditions, an airborne radar wave does not simply weaken when it strikes the ocean; it effectively ceases to exist within the first fraction of a millimeter. This total lack of penetration explains why traditional radar cannot scan beneath the surface of the sea.

## CONCLUSION

In this short introduction to the fundamentals of oceanography and sonar propagation, we have simplified the core mechanics of these complex naval sciences.

If there is only one tactical rule of thumb to carry away from this text, it is the fundamental law of acoustic refraction: the direction an acoustic ray bends depends entirely

on the vertical sound speed gradient. If the gradient is positive, the sound rays bend upward toward the surface; if the gradient is negative, the rays bend downward toward the seabed. Always remember the basic smiley chart, and never forget the core operational truth of underwater warfare: **sound is lazy, and it always curves toward the slowest medium.**

Navigating and fighting within this medium requires constant adjustments to account for shifting boundaries, thermal layers, and changing salinity profiles. On the Tactical Display Area (TDA) screen of your sonar station in Modern Naval Warfare (MNW), always monitor these acoustic pathways and track where caustic focal points form. Those specific zones represent your best opportunities to detect an elusive adversary—or to accidentally expose your own position if you are careless.



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## GLOSSARY OF TERMS

- **Absorption**

Conversion of acoustic energy into heat as a sound wave propagates through a medium.

- **Acoustic Impedance (Z)**

Resistance a medium presents to sound transmission, defined as the product of density and sound speed.

- **Ambient Noise**

Background acoustic energy in the ocean originating from natural and anthropogenic sources.

- **Amplitude**

Magnitude of pressure variation in a sound wave; determines perceived loudness.

- **Authigenic Sediments**

Seafloor deposits formed directly from dissolved substances precipitating out of seawater.

- **Bathymetry**

Measurement and mapping of seafloor depth and underwater topography.

- **Beamforming**

Signal-processing technique that aligns and sums hydrophone outputs to enhance coherent acoustic signals.

- **Bel / Decibel (dB)**

Logarithmic unit expressing ratios of acoustic power or pressure.

- **Biogenous Sediments**

Sediments derived from the skeletal remains or organic material of marine organisms.

- **Bottom Bounce**

Propagation path in which sound reflects off the seabed before reaching a receiver.

- **Caustic Zone**

Region where refracted sound rays converge, producing a local maximum in acoustic intensity.

- **Cavitation**

Formation and collapse of vapor bubbles around propellers or appendages, generating broadband noise.

- **Convergence Zone (CZ)**

Deep-ocean focusing region where refracted sound rays return to the surface at long range.

- **Critical Angle**

Incidence angle above which total reflection occurs when sound passes from a slower to a faster medium.

- **Cylindrical Spreading**

Geometric spreading loss occurring when sound is trapped between boundaries, reducing intensity with distance.

- **Deep Sound Channel (DSC / SOFAR)**

Mid-depth acoustic duct formed around the sound-speed minimum, enabling long-range propagation.

- **Density ( $\rho$ )**

Mass per unit volume of seawater, dependent on temperature, salinity, and pressure.

- **Detection Threshold (DT)**

Minimum processed signal level required for a sonar system to declare a detection.

- **Direct Path**

Acoustic path in which sound travels directly between source and receiver without boundary interaction.

- **Divergent Boundary**

Tectonic plate boundary where plates move apart, forming mid-ocean ridges.

- **Fermat's Principle**

Principle stating that waves travel along the path requiring the least time.

- **Halocline**

Layer in the water column characterized by a rapid change in salinity with depth.

- **Hydrothermal Vent**

Seafloor fissure emitting heated, mineral-rich water into the ocean.

- **Isothermal Deep Water**

Deep ocean layer where temperature remains nearly constant with increasing depth.

- **Mackenzie Equation**

Empirical formula used to estimate sound speed in seawater from temperature, salinity, and depth.

- **Mixing Layer / Surface Layer**

Upper ocean layer with uniform temperature and salinity due to wind and wave mixing.

- **Negative Gradient**

Condition where sound speed decreases with depth, causing rays to refract downward.

- **Passive SONAR**

Acoustic detection system that listens for sound without transmitting.

- **Positive Gradient**

Condition where sound speed increases with depth, causing rays to refract upward.

- **Pycnocline**

Layer of rapid density increase with depth.

- **Ray Theory**

Geometric model treating sound propagation as rays that obey Snell's law.

- **Reflection**

Return of acoustic energy from a boundary such as the sea surface or seabed.

- **Refraction**

Bending of sound rays due to spatial variations in sound speed.

- **Reliable Acoustic Path (RAP)**

Deep-ocean propagation path where rays refract downward then upward with relatively low transmission loss.

- **Salinity**

Concentration of dissolved salts in seawater, typically expressed in parts per thousand.

- **Scattering**

Diffuse redirection of sound energy caused by rough surfaces or inhomogeneities.

- **Seasonal Layer**

Temporary warm surface layer formed during summer due to solar heating.

- **Shadow Zone**

Region where refracted rays do not penetrate, resulting in very low acoustic intensity.

- **Snell's Law**

Law describing the relationship between sound-speed variation and ray bending at layer boundaries.

- **Sonic Layer Depth (SLD)**

Depth of maximum sound speed above the deep sound channel axis.

- **Sound Speed Profile (SSP)**

Vertical profile showing sound speed as a function of depth.

- **SOFAR Channel**

Historical term for the deep sound channel used for long-range acoustic propagation.

- **Spreading Loss**

Reduction in acoustic intensity due to geometric spreading of the wavefront.

- **Surface Bounce**

Reflection of sound from the sea surface.

- **Surface Duct**

Near-surface acoustic duct formed between the surface and the sonic layer depth.

- **Terrigenous Sediments**

Sediments derived from erosion and transport of material from continental landmasses.

- **Thermocline**

Layer of rapid temperature decrease with depth.

- **Transmission Loss (TL)**

Reduction in acoustic intensity due to spreading and absorption.

- **Transient Layer**

Short-lived temperature layer formed daily or seasonally.

- **Wavelength ( $\lambda$ )**

Distance between two successive wave crests; inversely proportional to frequency.

## REFERENCES

## HISTORY

- Ballantyne, Iain. 2018. *The Deadly Deep: The Definitive History of Submarine Warfare*. First Pegasus books hardcover edition. New York: Pegasus Books.
- Boyd, Carl, and Akihiko Yoshida. 2012. *The Japanese Submarine Force and World War II*. Annapolis: Naval Institute Press.
- Compton-Hall, Richard. 1982. *The Underwater War, 1939-1945*. Poole, Dorset : New York, N.Y: Blandford Press ; Distributed by Sterling Pub.
- Compton-Hall, Richard. 1983. *Submarine Boats: The Beginnings of Underwater Warfare*. Leicester: Windward.
- Davies, Roy. 1995. *Nautilus: The Story of Man under the Sea*. Annapolis, Md: Naval Institute Press.
- Friedman, Norman. 2021a. *British Submarines in the Cold War Era*. Havertown: Pen & Sword Books Limited.
- Friedman, Norman. 2021b. *U.S. Submarines through 1945: An Illustrated Design History*. Annapolis, Maryland: Naval Institute Press.
- Friedman, Norman. 2023. *U.S. Submarines since 1945: An Illustrated Design History*. Revised edition. Printed case edition. Annapolis, Maryland: Naval Institute Press.
- Köhl, Fritz, Eberhard Rössler, and Eberhard Rössler. 1991. *The Type XXI U-Boat*. Annapolis, Md: Naval Institute Press.
- Kopenhagen, Wilfried. 2001. *Soviet and Russian Nuclear Submarines*. Atglen, PA: Schiffer Pub.
- Preston, Antony. 1998. *Submarine Warfare*. London: Brown Books.
- Solomon, Louis P. 2003. *Transparent Oceans: The Defeat of the Soviet Submarine Force. United States?* publisher not identified.
- Tsvetkov, Pavel, ed. 2011. *Nuclear Power: Deployment, Operation and Sustainability*. Erscheinungsort nicht ermittelbar: IntechOpen.

## DESIGN

- Bays, Samuel, Abdalla Abou Jaoude, and George Borlolan. 2019. *Reactor Fundamentals Handbook*. doi:[10.2172/1615634](https://doi.org/10.2172/1615634).
- Burcher, Roy, and Louis Rydill. 1994. *Concepts in Submarine Design*. Cambridge [England] ; New York: Cambridge University Press.
- DiMercurio, Michael, and Michael Benson. 2003. *The Complete Idiot's Guide to Submarines*. Indianapolis, IN: Alpha.
- Friedman, Norman N., and N. Friedman. 1984. *Submarine, Design and Development*. London: Conway Maritime Press.
- Radkowsky, A. Ed. 1964. *NAVAL REACTORS PHYSICS HANDBOOK. VOLUME I. SELECTED BASIC TECHNIQUES*. doi:[10.2172/4007148](https://doi.org/10.2172/4007148).
- Torres, Félix, and Boris Danzer-Kantof. 2022. *Les Atomes de la Mer - la Propulsion Nucléaire Française, Histoire d'un Outil de Dissuasion*. Québec: Le Cherche Midi Editeur.

Initial Evaluation of Fuel-Reactor Concepts for Advanced LEU Fuel Development. INL, February 2020, 37p. [https://inldigitallibrary.inl.gov/sites/sti/sti/Sort\\_22041.pdf](https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_22041.pdf)

All at Sea with User Interfaces: From Evolutionary to Ecological Design for Submarine Combat Systems, Daniel Fay, Neville A Stanton, Aaron PJ Roberts. January 2019, *Theoretical Issues in Ergonomics Science* 201. DOI:10.1080/1463922X.2019.1582115

## ASW HISTORY

*The Submarine Pioneers* by Richard Compton-Hall, 1999, 182p. ISBN: 978-0750921541

*Submarine in Color* by Bill Guston and John W. Wood. 197, 200p ISBN: 978-0668041072

*Nautilus the Story of man under the sea* by Roy Davies. 1995, 239p. Naval Institute Press. ISBN: 978-1557506153

*John P. Holland, 1841-1914 Inventor of the Modern Submarine* by Richard Knowless, 1998, 221p. University of South Carolina Press. ISBN: 978-1570032363

*Going deep* by Laurence Goldstone. 2017, 352p, Pegasus Books. ISBN: 978-1681774299

*U-boat Century: German Submarine Warfare 1906-2006* by Jak M. Showell, 2006, 224p, Chatham Publishing. ISBN: 1-8617-6241-0.

*Hunters and Killers: Volume 1: Anti-Submarine Warfare from 1776 to 1943* by Norman C. Polmar and Estate of Edward C. Whitman. 2015, 224p. Naval Institute Press ISBN: 978-1591146896.

*Hunters and Killers: Volume 2: Anti-Submarine Warfare from 1943* by Norman C. Polmar and Estate of Edward C. Whitman. 2016, 272p. Naval Institute Press ISBN: 978-1612518978

*Sub Chaser* by Edward E. Brittingham, 2004, 287p, ASW Press. ISBN: 978-0972785921

*Tailships: The Hunt for Soviet Submarines in the Mediterranean, 1970-1973* by John Rodgaard. 84p - Europe@War series number 38. ISBN: 978-1914377099.

*Submarine (Tom Clancy's Military Reference)* by Tom Clancy and John Gresham, 368p, 2003, Penguin Publishing Group. ISBN: 978-0425190012

*Airborne Anti-Submarine Warfare: From the First World War to the Present Day* by Michael Glynn. 406p, 2022, Frontline Books, ASIN: B09WKZ3LHM

## SUBMARINE DESIGN

*Concepts in Submarine Design* by Roy Burcher and Louis J. Rydill, 1985. 404p, Cambridge University Press. ISBN: 978-0521559263

*Soviet Submarines: Design, Development, and Tactics.* by Jan S. Breemer. 194p, 1989, Janes Information Group. ISBN: 978-0710605269

*Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines* by Norman Polmar and Kenneth J. Moore. 541p, 2004, Potomac Books Inc. ISBN: 978-1574885941

*Astute Class Nuclear Submarine Owners' Workshop Manual: 2010 to date - Insights into the design, construction, and operation of the most advanced attack submarine ever operated by the Royal Navy* by Jonathan Gates. 192p, 2018, Haynes Publishing UK. ISBN: 978-1785210716

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